Results of IEA SHC Task 32: Subtask C: Phase Change Materials

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Abstract

Phase change materials (PCM) as heat storage theoretically offer an advantage compared to water stores on the one hand, when the cycling temperature is close around the phase change temperature and the phase change can be used quite often. Another application is the use of the subcooling effect of certain PCM for seasonal storage. The scope, in terms of general system aspects for IEA SHC Task 32, was solar heating and cooling systems for residential buildings, principally detached houses for one up to a few families. Additionally other promising heating or cooling systems were taken into consideration. Five projects dealing with PCM modules in solar combistores, seasonal storage with subcooled PCM and PCM in residential heating systems as space heating stores were investigated in the laboratory and by simulation studies. However, the investigations reported here showed only little advantages for macro-encapsulated PCM modules in combistores, PCM-stores with immersed heat exchangers and for PCM slurries for heat stores in solar combisystems and residential heating systems. The seasonal storage with subcooled PCM could be in principle a good solution. However the technical expenditure for this system is large.

1. The scope of IEA SHC Task 32, subtask C, phase change materials (PCM)

The scope, in terms of general system aspects, for Subtask C was the same as that for the whole of Task 32, namely solar heating and cooling systems for residential buildings, principally detached houses for one up to a few families. Buildings with a larger specific heat load (>100 kWh/(m^2a) for Zurich climate) are not considered. The main focus was to find storage solutions sized to achieve a significant solar fraction but also for other applications in the heat storage field for domestic housing, especially to reduce the cycling rate of conventional boilers.

Some solutions using PCM have already been tested in full scale pilot plants and some durable commercial products are already on the market for special applications (Cristopia, Rubitherm among others).

Detailed activities included

- the selection of suitable materials,
- the development of storage prototypes and
- the optimization of existing solutions in an integrated system such as the reference combisystem defined by Subtask A.

All solutions with PCM stores were compared to pure water stores.

Fig. 1 shows a classification of processes for PCM storage of heat, in Subtask C only the paraffins (analytical grade) and hydrated salts have been addressed.

In terms of temperature, the storage solutions have been limited to temperatures < 85°C, because the maximum needed temperature for the domestic applications with low temperature heating systems is the DHW demand with around 50°C. The phase change temperature of the materials chosen (mainly sodium acetate trihydrate, partly embedded in a graphite matrix to increase the thermal conductivity) is at about 58°C. For some other tests additional PCM with a lower phase change temperature was chosen (paraffin).

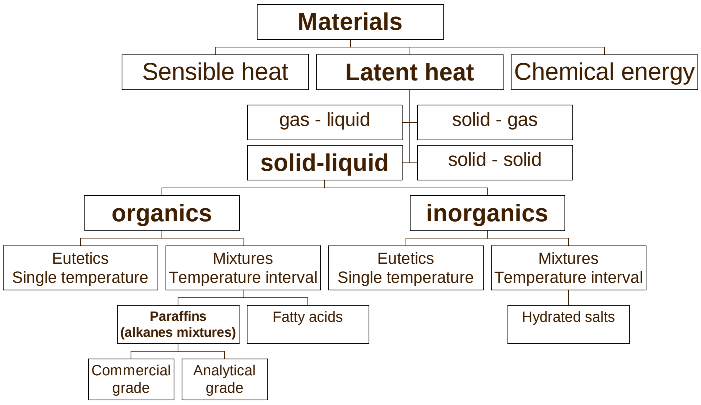


Fig. 1. Classification of energy storage materials [1].

Simulation models of the PCM storage component were developed for different types of PCM heat store philosophies, as no validated models were available for the simulation software TRNSYS at the beginning of the task. These models were validated by laboratory tests before being integrated into a system model within TRNSYS. Each Subtask was responsible to develop an appropriate tool, in order to enable an estimation of the performance of a system with the proposed storage concept.

2. Projects within Subtask C

There were five PCM related projects included in IEA SHC Task 32. A summary of these projects is given in Table 1.

Three projects dealt with macro-encapsulated PCM containers in water stores. All of these projects include the development of TRNSYS models for the PCM stores:

- At Lleida University, Spain, bottles and filled up heat exchangers of PCM material with graphite matrix for the enhancement of the heat conduction and increase of power input/output were tested. Applications are free-cooling and DHW tanks.
- At the University of Applied Sciences Western Switzerland in Yverdon-les-Bains/Switzerland a parametric study for the use of PCM in heat stores embedded in aluminium bottles for solar combisystems was carried out.
- The Institute of Thermal Engineering at Graz University of Technology performed tests and simulations with different PCM materials encapsulated in plastic tubes and steel containers for stores for conventional boilers to reduce the number of start-stop cycles of the burner.

The two other projects are slightly different:

- At the Department of Civil Engineering, Technical University of Denmark the use of super cooling of PCM materials for long-term heat storage was investigated with simulations. This project showed that a 10 m^3 only PCM seasonal storage using the supercooling effect is theoretically possible. Experimental setup assessed some assumptions on heat transfer in a bulk PCM tank
- The Institute of Thermal Engineering at Graz University of Technology performed tests and simulations with PCM-slurries of microencapsulated paraffins for stores for conventional boilers to reduce the number of start-stop cycles.

The above project is also dealing with heat exchangers immersed in PCM material

Table 1. Summary of prototype storage units studied in Subtask C.

Type of Technology	Material	Stage of Development	Investigating Institute
PCM seasonal storage using subcooling	$Na(CH_3COO)\cdot 3\ H_2O$	Lab prototype; Simulation model for store developed and seasonal simulations of the system were performed	Technical University of Denmark (DTU), Denmark
Macroencapsulated PCM in storage tank	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite	Lab prototype; Seasonal simulations of the system were performed, using the model developed by the Institute of Thermal Engineering, Graz Unviersity of Technology	University of Lleida, Spain
Macroencapsulated PCM in storage tank with integrated burner	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite	Lab prototypes; Simulation model for store developed and validated; Seasonal simulations of the system were performed according to the reference conditions from Subtask A	University of Applied Sciences Western Switzerland (HEIG-VD), Switzerland
Microencapsluated PCM slurry	Paraffin,	Lab prototypes, Development of simulation models for a store filled with slurry with various internal heat exchangers and flow/return pipes and an external heat exchanger with PCM slurry on one or both sides.	Graz University of Technology, (IWT-TU Graz), Austria
Macroencapsulated PCM in storage tank	Paraffin, $Na(CH_3COO)\cdot 3\ H_2O$ with/without graphite	Simulation model for store developed and validated; Seasonal simulations of the system were performed for various hydraulic schemes for heating systems in order to analyze the reduction of the boiler cycling rate compared to water stores.	Graz University of Technology, (IWT-TU Graz), Austria
Immersed heat exchanger in PCM	$Na(CH_3COO)\cdot 3\ H_2O$ without graphite	Simulation model for store developed and validated; Seasonal simulations of the system were performed for various hydraulic schemes for heating systems in order to analyze the reduction of the boiler cycling rate compared to water stores.	Graz University of Technology, (IWT-TU Graz), Austria

- The Institute of Thermal Engineering at Graz University of Technology performed tests and simulations with a bulk PCM tank with an immersed water-to-air heat exchanger for conventional boilers to reduce the number of start-stop cycles of the burner.

For a summary of these projects see Table 1; the main results are given in the following chapters.

3. Main results of Subtask C

3.1. Results of the laboratory measurements [2]

All storage solutions dealt with in Subtask C were only laboratory prototypes. Measured results and projected heat storage densities for units of 70 and 1000 kWh storage for single family houses are reported. The prototypes use either paraffins or sodium acetate trihydrate, but all of them had a phase change at about 58°C in order to provide space heating and domestic hot water. The system from HEIG-VD additionally uses a PCM with phase change at 27°C in the preheating zone of the buffer store.

The prototypes are intended for different applications. While the stores from HEIG-VD, Switzerland and University of Lleida, Spain are short term heat storages for solar combisystems, the store from the Technical University of Denmark is used as seasonal storage by making use of the subcooling effect in hydrated salts. The work of Graz University of Technology is dealing with very short term storage for boilers, to reduce start-stop cycles and emissions. For small short term storages one decisive factor is to deliver enough thermal power for the domestic hot water demand (26 kW e.g. for filling a bath tub of a single family residential building). This means high specific power and therefore either high thermal conductivity of the solid PCM and/or small distances for the heat transfer from PCM to the heat carrier. For larger stores this problem is far smaller due to the lower necessary specific power. The projects were financed partly from national and partly from European Union projects.

The storage density compared to water is strongly dependent on the temperature lift in the storage tank. For small temperature differences (50 – 70 °C) and a bulk PCM tank with immersed heat exchanger (like the store used at the Graz University of Technology), the store can be theoretically sized about 1/3 of the volume compared to water, if sodium acetate trihydrate is used as PCM. With this layout additionally about 20 kW thermal power can be delivered for the DHW production with less than 8 K heat loss. For the same PCM-material but macro-encapsulated and for a temperature lift from 25 to 85°C or 20 to 70°C in solar combisystems the store has the same size as a water store. For such cases there is even theoretically little benefit from PCM with respect to the store size.

In terms of material cost, all materials are expensive compared to water, ranging from pure sodium acetate with about 1 €/kg, paraffin with about 2 €/kg (including nucleation enhancer) to sodium acetate trihydrate with graphite and nucleation enhancers with about 3 - 4 €/kg. The cost for the whole storage system has not been estimated here.

3.2. Results of System simulations

Four simulation studies were performed in Subtask C. Three of them were using more or less the reference conditions defined in Subtask A [3]. One of them dealt with a complete different application to reduce boiler cycling by introducing a PCM store.

The simulation results from HEIG-VD in Yverdon-les-Bains, Switzerland concerning the advantage of macroencapsulated PCM in solar combisystems are shown in Fig. 2 [4]. It should be reminded that the proposed system has been analysed only from the simulation side, where a water tank storage filled only with water or filled with water + PCM (paraffin RT35) is compared.

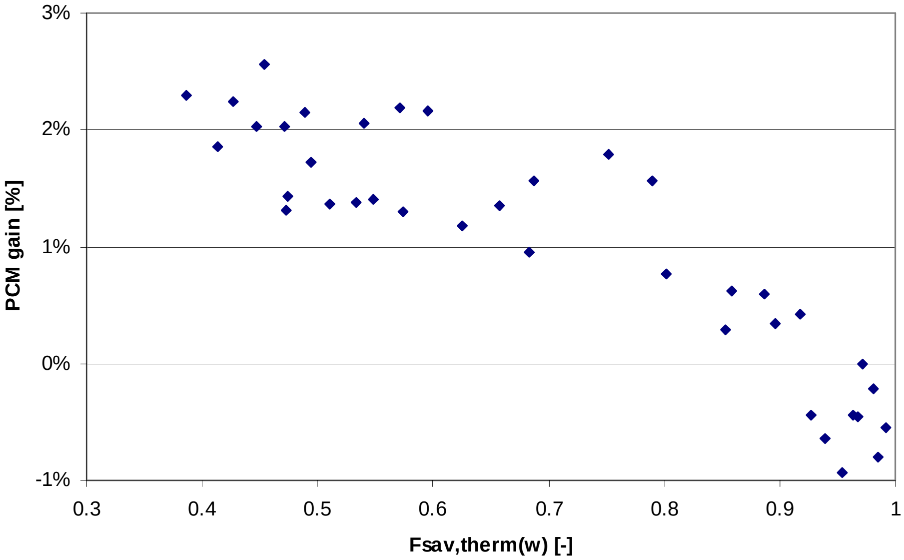


Fig. 2. Difference between pure water and water + PCM system. (PCM gain = $F_{sav,therm(W+PCM)}/F_{sav,therm(W)} - 1$)

To evaluate the impact of the PCM on the performances, it is possible to define the energy gain between the $F_{sav,therm}$ for the tank with PCM ($F_{sav,therm(W+PCM)}$) and only with water ($F_{sav,therm(W)}$). If this gain is higher than 0, then the PCM brings an advantage. As it can be seen in Figure 3, the gain due to using PCM is low. A decrease of the RATIO according to the increase of the $F_{sav,therm}$ can also be noticed. But it should be remembered, that when the $F_{sav,therm}$ is high, the solar installation is oversized. As it can be seen, adding a PCM becomes less interesting when the solar system is oversized. This is due to the fact, that when oversized, the storage of heating is less relevant.

The **fractional thermal energy savings** $f_{sav,therm}$ are a measure of the percentage of the auxiliary (non-solar) energy input for heating that can be reduced by the solar system. This term does not account for electricity use unless it is used directly for heating. The efficiency of electricity production and distribution η_{el} is 0.4 in all cases. Hereby Q_{boiler} and $Q_{el,heater}$ are the energy inputs of the solar combisystem with respective efficiencies η_{boiler} and η_{el}. $Q_{boiler,ref}$ defines the energy input of a boiler of a defined conventional heating system with an efficiency of $\eta_{boiler,ref}$ [3].

$$f_{sav,therm} = 1 - \frac{\dfrac{Q_{boiler}}{\eta_{boiler}} + \dfrac{Q_{el,heater}}{\eta_{el}}}{\dfrac{Q_{boiler,ref}}{\eta_{boiler,ref}}} \qquad \text{(Equation 1)}$$

According to the additional cost of adding the PCM and the environmental impacts results described in [2], this system with PCM does not show a substantial benefit compare to a storage tank filled only with water.

Only the long term heat storage with subcooled liquid PCM (BYG DTU, Department of Civil Engineering, Denmark, Fig. 3 [5]) shows the possibility to achieve 100 % solar fraction with PCM store volumes of about 10 m³ for a 135 m² floor area passive houses (15 kWh/m²a space heating energy demand). Water stores have to be far bigger to achieve the 100 % solar fraction. 80 – 90 %

solar fraction can be achieved also with water stores of 5 - 10 m³. Taking into account the long term heat losses of water stores the size reduction is far bigger.

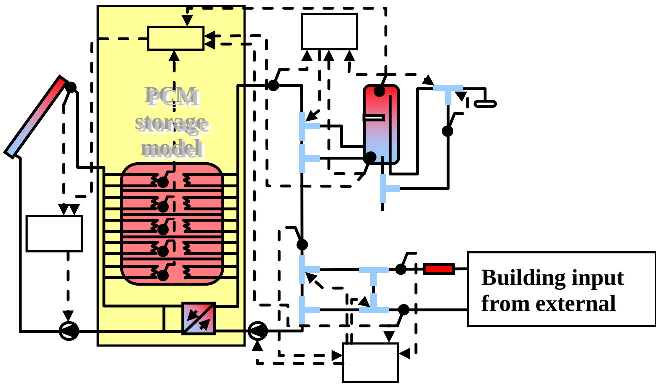


Fig. 3. Simulation model of BYG DTU, Department of Civil Engineering, Denmark [5]

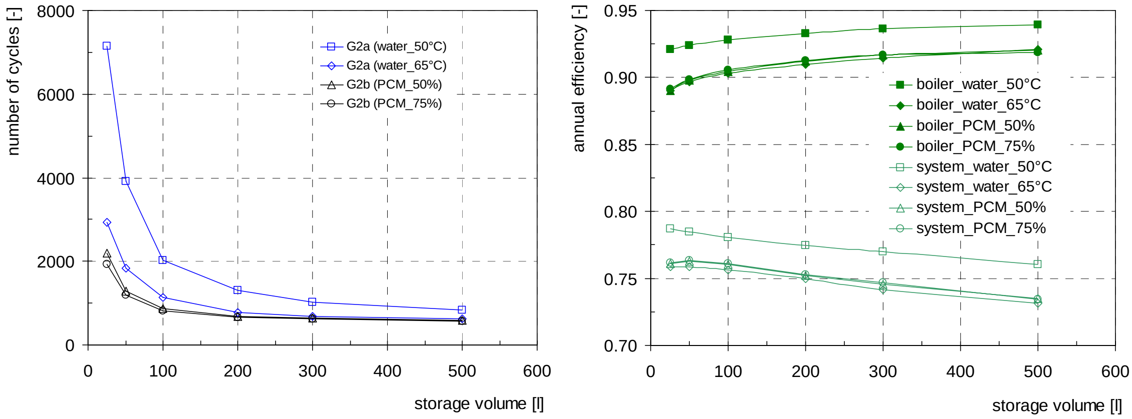
At the Institute of Thermal Engineering (IWT), Graz University of Technology, Austria different hydraulic systems were investigated in terms of their ability to reduce boiler cycling operation [6]. In the following a description of the hydraulic systems, which are used in the simulations, is given. Table 2 shows a summary of all simulated concepts.

Table 2: Summary of all simulated system concepts [6]

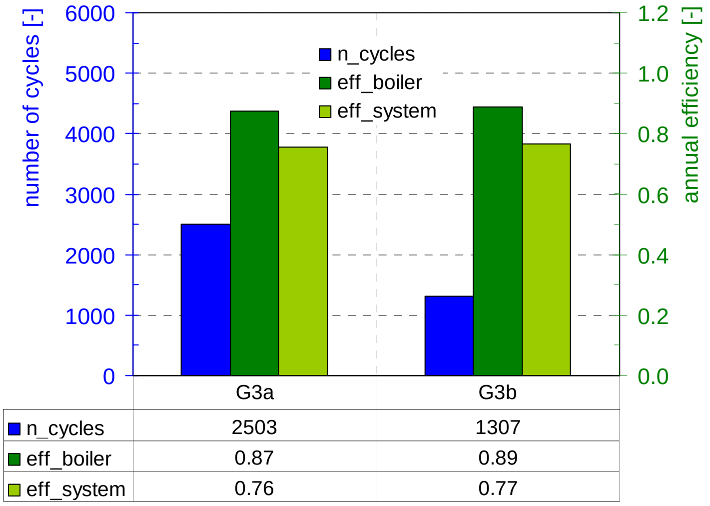
System	Boiler type	Type of space heating store	Type of DHW preparation	Hydraulic integration and control of boiler
System Category 1: no space heating storage , DHW tank				
G1a	Gas	No storage	DHW tank	Boiler temp. controlled as a function of the ambient temp., throttle control
G1b	Gas	No storage	DHW tank	Constant boiler temp., flow temp. control via mixing valve
G1c	Gas	No storage	DHW tank	Constant boiler temp., flow temp. control via mixing valve, hydraulic switch
P1	Pellets	No storage	DHW tank	Constant boiler temp., flow temp. control via mixing valve, hydraulic switch, return temp. control
System Category 2: space heating storage , DHW tank				
G2a	Gas	Water storage	DHW tank	Constant boiler temp., flow temp. control via mixing valve
G2b	Gas	Water storage + PCM modules	DHW tank	Constant boiler temp., flow temp. control via mixing valve
P2a	Pellets	Water storage	DHW tank	Constant boiler temp., flow temp. control via mixing valve, return temp. control
P2b	Pellets	Water storage + PCM modules	DHW tank	Constant boiler temp., flow temp. control via mixing valve, return temp. control
System Category 3: space heating storage , instantaneous preparation of DHW				
G3a	Gas	Water storage	Instantaneous	Constant boiler temp., flow temp. control via mixing valve
G3b	Gas	Bulk PCM storage	Instantaneous	Constant boiler temp., flow temp. control via mixing valve

The results for the system with water storage (G2a) and for systems with water storage with integrated PCM modules (G2b) are shown in Fig. 4 for different storage volumes. In comparison to the systems without buffer storage the number of start-stop cycles is reduced strongly. Even with the smallest volume of only 25 litres of water a reduction of about 70 % (set temp. 50°C) or 90 % (set temp. 65°C) can be achieved. With increasing storage volumes the number of cycles decreases, whereby the potential for a further reduction is low for volumes above 200 litres. Because of the lower utilized temperature difference the number of cycles is higher with a boiler temperature of 50°C in comparison to 65°C. On the other hand the higher temperatures decrease the annual efficiencies of the condensing boiler by 2-3 %.

The integration of PCM modules (boiler set temp. 65°C in all cases) allows an enhancement of the storage capacity, resulting in a further decrease of the number of start-stop cycles especially with small storage volumes. There are only minor differences between the PCM volume fractions of 50 and 75 %. The integration of PCM modules hardly influences the annual efficiencies of the boiler and the system (Fig. 4, right).



Fig, 4. Gas boiler: annual number of start-stop cycles (left) and annual efficiencies (right) for different storage volumes for systems with water storage (G2a) and for systems with water storage with integrated PCM modules (G2b)



	G3a	G3b
■ n_cycles	2503	1307
■ eff_boiler	0.87	0.89
■ eff_system	0.76	0.77

Fig. 5. Annual number of start-stop cycles and annual efficiency for the systems G3a (water storage) and G3b (bulk PCM storage)

Figure 5 shows the number of start-stop cycles and the annual efficiencies for the system G3a (water storage) and the system G3b (bulk PCM storage). Due to the higher storage capacity of the PCM storage (assuming the same volume of 45 litres) in system G3b the number of cycles can be reduced by 50 % compared to system G3a. The annual efficiency of the boiler is also slightly higher, which is a result of the lower amount of heat produced in start-stop operation due to the higher storage capacity.

4. Conclusion

Phase change materials as heat storage theoretically offer an advantage compared to water stores, when the cycling temperature is close around the phase change temperature and the phase change can be used quite often. The other possible application is the use of the subcooling effect for seasonal storage. However, the investigations reported here showed only little advantages for macro-encapsulated PCM modules in combistores, PCM-stores with immersed heat exchangers and for PCM slurries for heat stores in solar combisystems and residential heating systems. The seasonal storage with subcooled PCM could be in principle a good solution. However the technical expenditure for this system is large.

References

[1] A. Abhat, (1983), Low temperature latent heat thermal energy storage: heat storage materials, Solar Energy 30 (1983) 313-332.

[2] W. Streicher, (ed). (2008), Laboratory Prototypes of PCM Storage Units, Report C4, of IEA Solar Heating and Cooling programme - Task 32, “Advanced storage concepts for solar and low energy buildings”, IEA-SHC (http://www.iea-shc.org/task32/publications/index.html)

[3] H. Heimrath, M. Haller, (2008), The Reference Heating System, the Template Solar System, Report A2, of IEA Solar Heating and Cooling programme - Task 32, “Advanced storage concepts for solar and low energy buildings”, IEA-SHC (http://www.iea-shc.org/task32/publications/index.html)

[4] S. Citherlet, J. Bony, (2008), System Simulation Report, System : HEIG-VD-W and HEIG-VD-PCM, Report C6.1, of IEA Solar Heating and Cooling programme - Task 32, “Advanced storage concepts for solar and low energy buildings”, IEA-SHC (http://www.iea-shc.org/task32/publications/index.html)

[5] J.M. Schultz, (2008), System Simulation Report, PCM with supercooling, Report C6.2, of IEA Solar Heating and Cooling programme - Task 32, “Advanced storage concepts for solar and low energy buildings”, IEA-SHC (http://www.iea-shc.org/task32/publications/index.html)

[6] A. Heinz, (2008), System Simulation Report, System: PCM storage to reduce cycling rates for boilers, Report C6.3, of IEA Solar Heating and Cooling programme - Task 32, “Advanced storage concepts for solar and low energy buildings”, IEA-SHC (http://www.iea-shc.org/task32/publications/index.html)