Laboratory Prototypes of PCM Storage Units

A Report of IEA Solar Heating and Cooling programme - Task 32

“Advanced storage concepts for solar and low energy buildings”

Report C3 of Subtask C

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Edited by:
Wolfgang Streicher

Contributions from:
Jørgen M. Schultz
Cristian Solé & Luisa Cabeza
Jacques Bony
Andreas Heinz

Task 32
Storage

SHC
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Report C3 of Subtask C

Laboratory Prototypes of PCM Storage Units

by

Wolfgang Streicher (Editor)*

Project data by:

Bony, J, Citherlet, S., HEIG-VD, Yverdon-les-Bains, Switzerland,
Cabeza, L., University of Lleida (Spain),
Schultz, J., M., Furbo, S., BYG DTU, Department of Civil Engineering
Heinz, A., Institute of Thermal Engineering, Graz University of Technology

A technical report of Subtask C

IWT TU Graz
Institut für Wärmetechnik

*Institute of Thermal Engineering
Graz University of Technology Austria

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

IEA Solar Heating and Cooling Programme

The *International Energy Agency* (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris. Established in 1974 after the first "oil shock," the IEA is committed to carrying out a comprehensive program of energy cooperation among its members and the Commission of the European Communities.

The IEA provides a legal framework, through IEA Implementing Agreements such as the *Solar Heating and Cooling Agreement*, for international collaboration in energy technology research and development (R&D) and deployment. This IEA experience has proved that such collaboration contributes significantly to faster technological progress, while reducing costs; to eliminating technological risks and duplication of efforts; and to creating numerous other benefits, such as swifter expansion of the knowledge base and easier harmonization of standards.

The *Solar Heating and Cooling Programme* was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia
Austria
Belgium
Canada
Denmark
European Commission
Germany
Finland
France
Italy
Mexico
Netherlands
New Zealand
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Spain
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A total of 39 Tasks have been initiated, 30 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

The Tasks of the IEA Solar Heating and Cooling Programme, both underway and completed are as follows:

Current Tasks:

Task 32	*Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33	*Solar Heat for Industrial Processes*
Task 34	*Testing and Validation of Building Energy Simulation Tools*
Task 35	*PV/Thermal Solar Systems*
Task 36	*Solar Resource Knowledge Management*
Task 37	*Advanced Housing Renovation with Solar & Conservation*
Task 38	*Solar Assisted Cooling Systems*
Task 39	*Polymeric Materials for Solar Thermal Applications*

Completed Tasks:

Task 1	*Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2	*Coordination of Solar Heating and Cooling R&D*
Task 3	*Performance Testing of Solar Collectors*
Task 4	*Development of an Insolation Handbook and Instrument Package*
Task 5	*Use of Existing Meteorological Information for Solar Energy Application*
Task 6	*Performance of Solar Systems Using Evacuated Collectors*
Task 7	*Central Solar Heating Plants with Seasonal Storage*
Task 8	*Passive and Hybrid Solar Low Energy Buildings*
Task 9	*Solar Radiation and Pyranometry Studies*
Task 10	*Solar Materials R&D*
Task 11	*Passive and Hybrid Solar Commercial Buildings*
Task 12	*Building Energy Analysis and Design Tools for Solar Applications*
Task 13	*Advance Solar Low Energy Buildings*
Task 14	*Advance Active Solar Energy Systems*
Task 16	*Photovoltaics in Buildings*
Task 17	*Measuring and Modeling Spectral Radiation*
Task 18	*Advanced Glazing and Associated Materials for Solar and Building Applications*
Task 19	*Solar Air Systems*
Task 20	*Solar Energy in Building Renovation*
Task 21	*Daylight in Buildings*
Task 23	*Optimization of Solar Energy Use in Large Buildings*
Task 22	*Building Energy Analysis Tools*
Task 24	*Solar Procurement*
Task 25	*Solar Assisted Air Conditioning of Buildings*
Task 26	*Solar Combisystems*
Task 28	*Solar Sustainable Housing*
Task 27	*Performance of Solar Facade Components*
Task 29	*Solar Crop Drying*
Task 31	*Daylighting Buildings in the 21st Century*

Completed Working Groups:
CSHPSS, ISOLDE, Materials in Solar Thermal Collectors, and the Evaluation of Task 13 Houses

To find Solar Heating and Cooling Programme publications and learn more about the Programme visit **www.iea-shc.org** or contact the SHC Executive Secretary, Pamela Murphy, e-mail: pmurphy@MorseAssociatesInc.com

September 2007

What is IEA SHC Task 32

“Advanced Storage Concepts for solar and low energy buildings” ?

The main goal of this Task is to investigate new or advanced solutions for storing heat in systems providing heating or cooling for low energy buildings.

The first objective is to contribute to the development of advanced storage solutions in thermal solar systems for buildings that lead to high solar fraction up to 100% in a typical 45N latitude climate.

The second objective is to propose advanced storage solutions for other heating or cooling technologies than solar, for example systems based on current compression and absorption heat pumps or new heat pumps based on the storage material itself.

Applications that are included in the scope of this task include:

1. new buildings designed for low energy consumption
2. buildings retrofitted for low energy consumption.

The ambition of the Task is not to develop new storage systems independent of a system application. The focus is on the integration of advanced storage concepts in a thermal system for low energy housing. This provides both a framework and a goal to develop new technologies.

The Subtasks are:
Subtask A: Evaluation and Dissemination
Subtask B: Chemical and Sorption
Subtask C: Phase Change Materials
Subtask D: Water tank solutions

Duration
July 2003 - December 2007.

www.iea-shc.org look for Task32

IEA SHC Task 32 Subtask C

"Storage with Phase Change Materials"

This report is part of Subtask C of the Task 32 of the Solar Heating and Cooling Programme of the International Energy Agency dealing with solutions of storage based on phase change materials or "PCMs".

The density of storage compared to water is theoretically 1.2 to 5 depending on the temperature range of comparison.
Small temperature differences will favor PCM solutions, where as larger temperature ranges, 30 to 60 K and more will probably favor sensible storage in water.

The topics of PCM is not completely new for solar energy storage but the way Task 32 has handled it is new. From material to system and simulation, the process was application oriented: a solar combisystem has a target.
Can PCM storage do better than water tanks ?

PCM could also be used to reduce the cycling of boilers in a small volume tank. This new idea was also investigated in Task 32 in a project bringing more insight on the usefulness of PCMs in storing heat and power.

The report does not cover all aspects of the topic since the rules of an IEA SHC Task is that participating countries share information on projects they decide to bring in the Task.
Projects presented in this report reflects the knowledge of the participating body presenting the project.

The Operating Agent would like to thank the authors of this document for their implication in the search of future storage solutions for solar thermal energy, the key to a solar future for the heating and cooling of our buildings.

Jean-Christophe Hadorn

Operating Agent of IEA SHC Task 32
For the Swiss Federal Office of Energy

BASE Consultants SA - Geneva
jchadorn@baseconsultants.com

Executive Summary

Six laboratory prototypes of phase change material storage are described in this report. 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 have 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. Whereas the stores from HEIG-VD, Switzerland and University of Lleida, Spain are short term heat storages for solar combi- and domestic hot water systems, the store from the Technical University of Denmark is used as seasonal storage by making use of the subcooling effects in hydrated salts. The work of Graz University of Technology is dealing with very short term storage for boilers, to reduce the cycling rate and the 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 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 lower specific power. The projects are 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 immersed heat exchanger for the store of Institute of Thermal Engineering of Graz University of Technology can be sized about 1/3 of the volume compared to water by using sodium acetate trihydrate. For the same PCM-material but macro-encapsulated and for a temperature lift from 25 to 85 or 20 to 70°C in solar combisystems the store has the same size as a water store. For such cases, there is only little benefit from PCM with respect to store size.

For the seasonal storage of PCM the comparison to water stores is not as simple, because there are no heat losses of the subcooled PCM store. Compared to the theoretical heat storage of water without heat losses the PCM store can be reduced by about 30 %. Taking into account the longterm heat losses of water stores the size reduction is far bigger.

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

Phase change materials as heat storage 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. The other possible application is the use of the subcooling effect for seasonal storage. The investigations reported here showed only little advantages for macro-encapsulated PCM modules in combistores and for PCM slurries for solar combisystem heat stores.

Contents

INTRODUCTION

There are five PCM related projects included in Task 32:

Three projects deal 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 of PCM material with graphite matrix for the enhancement of the heat conduction and increase of power input/output are tested. Applications are free-cooling and DHW tanks.
- At the Applied University of West-Switzerland in Yverdon-les-Bains/Switzerland a parametric study for the use of PCM in heat stores for solar combisystems is carried out.
- The Institute of Thermal Engineering at Graz University of Technology performs 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 is investigated with simulations.
- The Institute of Thermal Engineering at Graz University of Technology performs tests and simulations with PCM-slurries of microencapsulated paraffins for stores for conventional boilers to reduce the number of start-stop cycles. TRNSYS modules are developed 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.

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

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

A summary of these projects is given in Table 1.1, and the detailed results are given in the following chapter. For each of them the main characteristics are described and the test results from the lab prototype are given. The resulting key figures for the prototypes (listed below) are presented together with projected sizes and heat storage densities for hypothetical stores with 70 and 1000 kWh storage for single family homes. The former represents a short term store whereas the latter represents a long term store. In the final section the prototypes are compared in terms of energy density and material cost.

Table 1.1 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	Technical University of Denmark (DTI), Denmark
Macroencapsulated PCM in storage tank	$Na(CH_3COO)\cdot 3\,H_2O$ + graphite	Lab prototype	University of Lleida, Spain
Macroencapsulated PCM in storage tank with integrated burner	$Na(CH_3COO)\cdot 3\,H_2O$ + graphite	Lab prototype	Applied University of West-Switzerland (HEIG-VD), Switzerland
Microencapsluated PCM slurry	Paraffine,	Lab prototypes	Graz University of Technology, (IWT-TUGraz), Austria
Macroencapsulated PCM in storage tank	Paraffine, $Na(CH_3COO)\cdot 3\,H_2O$ with/without graphite	Lab prototypes	Graz University of Technology, (IWT-TUGraz), Austria
Immersed heat exchanger in PCM	$Na(CH_3COO)\cdot 3\,H_2O$ without graphite	Lab prototypes	Graz University of Technology, (IWT-TUGraz), Austria

1.1 Definitions

The following terms used in this report are defined here.

Energy density of the material is often dependent on the operating conditions of the unit in which the material is used. This is defined together with storage density for each of the units.

Energy density of the material (NRJ4.1)
This is the ratio of the storage capacity to the volume of the active substance when phase change takes place. In this context phase change means in terms of the design operating conditions of the prototype store and not the theoretical maximum of the material. During operation the store will not always operate over the full range of loading under all conditions. This value indicates the maximum value expected during normal operation and not an average value.

Energy density of prototype store (NRJ4.2)
This is the ratio of the storage capacity to the volume of all storage vessels required in the prototype unit including pipes for transfer between the various vessels including any separate vessels for heat exchange. This represents the practical heat storage density in the prototype storage and is again related to the maximum storage during normal operation, and not an average.

Floor space required
This is the “footprint” of the storage unit including all vessels, valves and pumps necessary for its operation.

Relative density compared to water (25-85°C) NB Another temperature range could be used here if the application would be within a different range. The respective Table and the values below then were changed.
This is the ratio of the storage capacity of the prototype store to that of an equivalent water store used in the temperature range 25-85°C (69.2 kWh/m^3).

Estimated size for 70 / 1000 kWh store
This is an estimate of the volume that the storage unit would have, including all parts necessary for the same design charging rate and load as the prototype, if it were to have a storage capacity of 70 or 1000 kWh – for the same conditions and performance as the prototype.

Charge / Discharge Rate
These are the design charge / discharge rates for the prototype and are a measure of the heat exchange transfer rate rather than the storage capability. They should be the maximum values, but if these maximum values are only valid for part of the time, then a range is given.

Boundary Conditions
The boundary conditions are given for all relevant parameters such as temperature, degree of loading and heating rates.

2 PROTOTYPE STORAGE UNITS

2.1 State of development of the work with seasonal PCM heat storage at the Department of Civil Engineering, Technical University of Denmark (DTU)

Jørgen M. Schultz & Simon Furbo. Department of Civil Engineering, Tech. Univ. of Denmark

2.1.1 Background

The background for this work is the idea of a seasonal thermal storage based on the phase change material sodium acetate trihydrate with active use of supercooling as a measure to achieve a partly heat loss free thermal storage. The effect of supercooling allows a melted part of the storage to cool down below the melting point without solidification preserving the heat of fusion energy. If the supercooled storage reaches the surrounding temperature no heat loss will take place until the supercooled salt is activated. The choice of sodium acetate Trihydrate is based on the convenient melting temperature at 58 °C, which makes it suitable for both domestic hot water preparation and space heating, and its ability of stable supercooling. Figure 2.1.1 shows the heat storage capacity of sodium acetate trihydrate compared to water as well as the effect of supercooling.

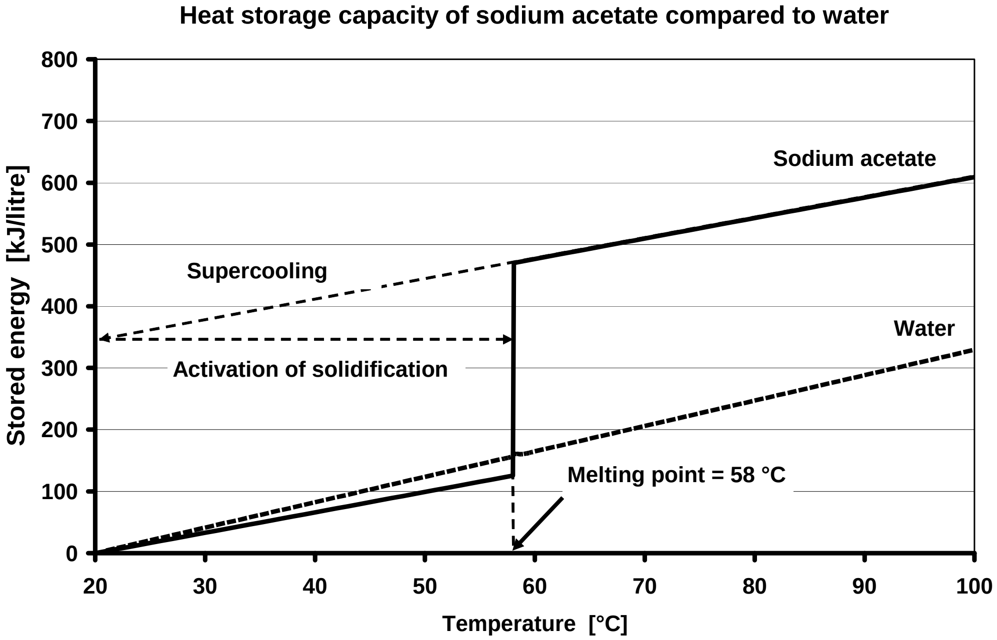

Figure 2.1.1 Diagram showing the heat storage capacity of sodium acetate trihydrate compared to water and the supercooling effect.

2.1.2 Design and Operating Principles

The heat storage concept is developed to be used for a seasonal heat storage able to fully cover both the space heating and the domestic hot water demand in a solar low energy building. The simulations on an ideal heat storage solution show that this would be possible in a Danish climate with a PCM storage volume of 6 m^3. However, before a full size prototype will be made and tested a lot of practical issues have to be tested in a much smaller laboratory prototype. Therefore the laboratory prototype is developed primarily to investigate and gain experience with:

- the handling of melted and supercooled sodium acetate trihydrate
- the supercooling process
- different methods for activating the solidification
- heat transfer to and from the sodium acetate trihydrate
- insulation needs

In order to understand the laboratory prototype design the concept for the seasonal storage is briefly described below.

2.1.2.1 Seasonal heat storage design for simulations

Figure 2.1.2 shows the total solar heating system used for the simulations of the seasonal heat storage performance. The system is made up of a solar collector loop and a load loop interconnected by the heat of fusion storage and a heat exchanger.

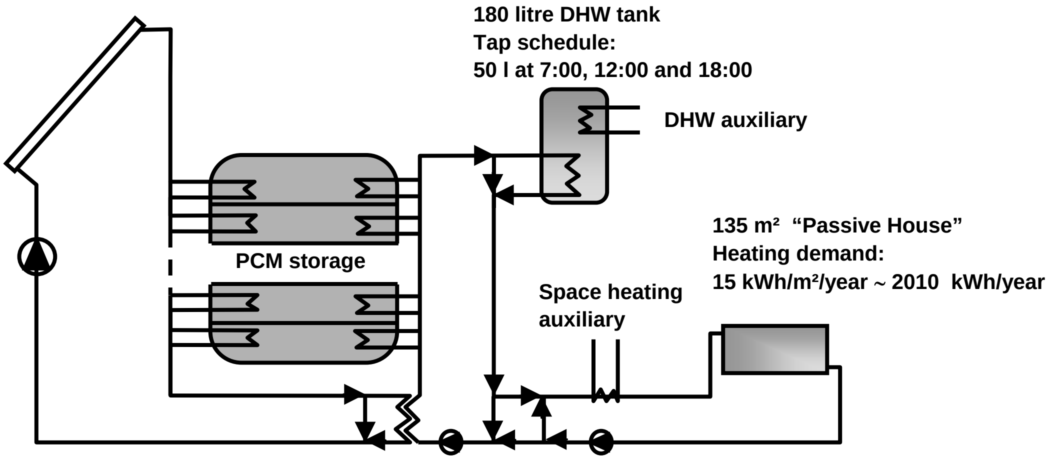

Figure 2.1.2 Solar heating system related to the seasonal PCM storage.

The system has two individual heat storages – a heat of fusion storage and a 180 litres domestic hot water storage with water as storage medium. The DHW water storage makes it possible to fulfil the power requirement related to DHW draw offs, which will be difficult to achieve by direct discharging of the PCM storage. The solar collector loop can transfer energy to the PCM storage and/or the load loop through the heat exchanger. Depending on the demand the load loop fluid can be heated by discharge of the PCM-storage.

The PCM storage is made up of a number of individual sections, which can be fully controlled with respect to charging, discharging and activation of solidification if in a supercooled state. Each section is considered thermally independent of each other but heat loss to the surroundings is accounted for. The purpose of the subsections is to avoid activating the total volume of supercooled PCM at one time, i.e. the subsections make it possible to match the demand in a more efficient way. Electrical heaters supply auxiliary energy for DHW and

space heating (if required). The space heating system is a low-temperature system e.g. floor heating with a constant return temperature of 25°C.
When solar energy from the collectors is available the control strategy is:

- If possible the DHW storage is heated until a temperature of 55°C is reached in the bottom of the storage by-passing the PCM storage.
- Next the space heating demand is covered directly - if possible. In case the solar collector fluid temperature is at a level where it allows for both heating of a section in the PCM storage and covering the space heating demand this will be done.
- If the hot water tank temperature is high enough and no space heating demand is present the PCM storage will be charged one section at the time until fully melted (if possible). After all sections are melted the DHW storage is charged until a maximum temperature of 70 °C has been reached. The charging of the PCM storage will continue until a maximum storage temperature of 100°C is reached.

When no solar energy from the collectors is available and a heating demand is present the control strategy is:

- If the DHW storage requires energy, if possible a liquid PCM storage section with a temperature higher than 55°C is discharged. If no liquid storage section fulfilling the requirements is present the control looks for a solidified section with a temperature higher than 55°C. If this also fails, the control looks for a supercooled section that can be activated in which case the storage section temperature immediately increases to the melting temperature (58°C) and can be discharged. The supercooled section with the highest temperature is used.
- If only energy for the space heating is required the same strategy is used, but the governing temperature is the required supply temperature in the space-heating loop.

2.1.2.2 Laboratory heat storage prototype

An important part of the laboratory experiments is how to handle large quantities of sodium acetate trihydrate with respect to melting and afterwards filling the melted sodium acetate trihydrate into the containers forming the subsections in the final storage.

Figure 2.1.3 shows the equipment used to melt the sodium acetate trihydrate. It consists of a stainless steel mantle tank, where hot water can be circulated through the mantle in order to melt the sodium acetate trihydrate. The inner tank has a volume of approximately 135 litres. A proper melting of the salt requires the salt to be stirred during the melting process, which is obtained by circulation of the melted salt from the bottom to the top through an external pipe connection and a tube pump. The external pipe connection is equipped with electric heating cables to avoid solidification of partly melted salt in the pipes. The external pipe connection and tube pump is also used to tap melted sodium acetate trihydrate into the subsection containers for the laboratory heat storage. The tube pump is started when the measured temperature in the container has been at the melting temperature for approximately 6 hours.

The melting container has also been used to test the stable supercooling ability of large volumes of sodium acetate trihydrate by turning off the water heating circuit and let the container cool down.

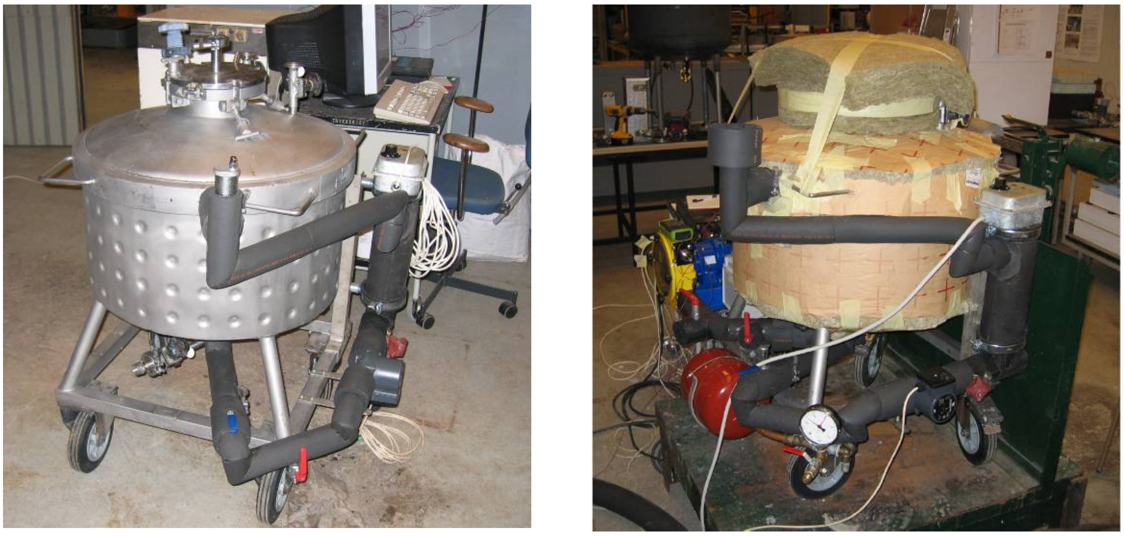

Figure 2.1.3 Left: Stainless steel mantle tank with the water heating loop connected
Right: Insulated mantle tank with both water heating loop and salt loop connected. The tube pump can be seen in the back to the left (yellow and blue).

The small scale laboratory PCM storage prototype is made up of 3 sodium acetate trihydrate filled subsections and 5 water filled sections as shown in Figure 2.1.4. The water filled sections act as heat exchangers and they are connected to a water loop that either can be heated to simulate the collector loop or cooled to simulate the discharge loop. This set-up makes it possible to investigate different charge and discharge modes, e.g. charge the salt from the bottom and discharge from the top, charge and discharge from the bottom only, charge and discharge from both top and bottom, etc…

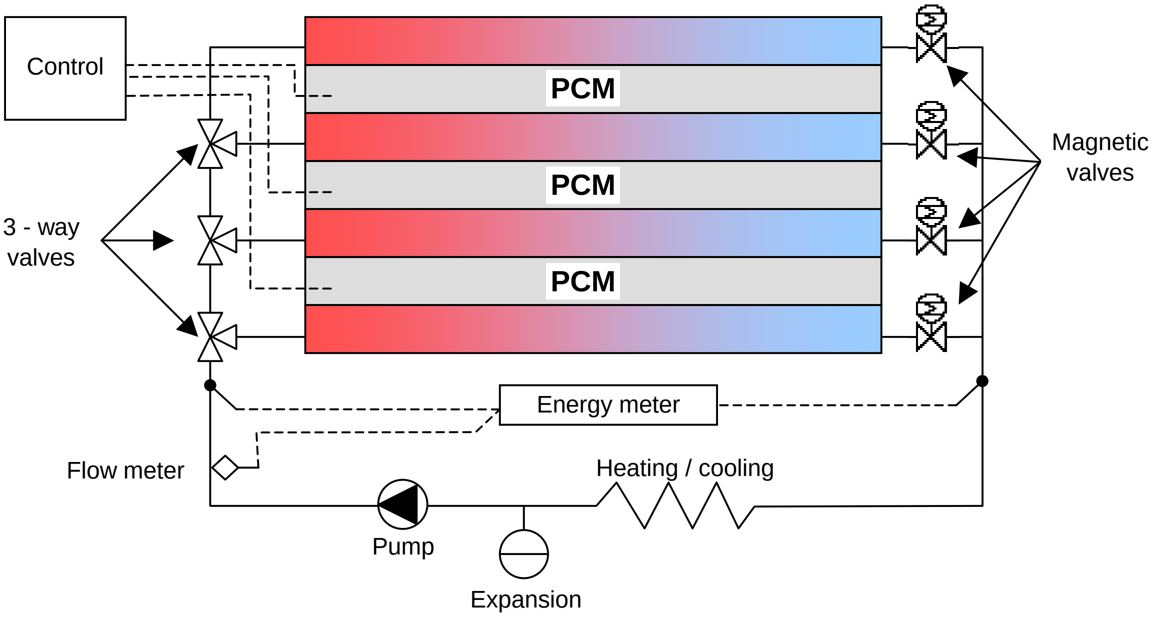

Figure 2.1.4 Schematic drawing of the small scale laboratory PCM storage prototype.

The different subsections shown in Figure 2.1.4 are made of sealed laminated plastic foil bags as an attempt to minimise the “parasitic thermal capacity”, i.e. the thermal capacity surrounding the salt solution, which could have a significant impact on the storage performance when activating the solidification of the supercooled salt. Furthermore, the plastic foil bags are flexible and will be able to follow the expansion and contraction of the salt hydrate during its phase change. This is of special importance to achieve a high heat transfer rate when the PCM subsection is charged or discharged from the top. Finally, the plastic bag solution is very cheap compared to e.g. a stainless steel solution.

The laminated plastic foil consists of 4 layers: PETP 12μm/ Aluminium 9μm/ PETP 12μm/ LLDPE 80μm. The foil has very high water vapour barrier properties and can resist temperatures above 100 °C. Each plastic bag measures approximately $1.0 \times 0.6 \times 0.03$ m^3 and the internal volume when filled is approximately 15 litres. Two tubes with screw caps are welded into the edge sealing of the bags positioned in two diagonal corners to obtain the best possible flow distribution in the water filled sections. The tubes in the PCM sections are used for filling the bags and for passing temperature sensors into the salt respectively.

The 7 bags are laid on top of each other according to Figure 2.1.4 and positioned in a box made of plywood to keep the bags in place. Figure 2.1.5 – 2.1.6 show some details of the laboratory prototype.

Fig. 2.1.5 Plastic foil bag in plywood box before filling with melted salt solution.

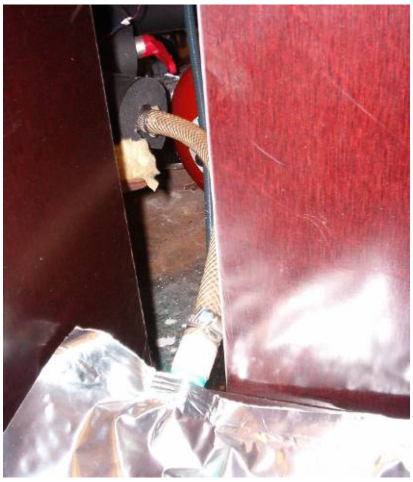

Fig. 2.1.6 Filling of plastic foil bag from the melting tank.

2.1.3 Laboratory Test Results

2.1.3.1 Melting and supercooling in melting tank

The first phase of the laboratory tests has been focused on melting approximately 70 kg of sodium acetate trihydrate and afterwards let it supercool in the large melting tank.

The melting was performed by circulation of 85 °C hot water through the mantle of the melting container. The melting process required about 2 days before stationary temperatures in the melted salt was obtained. The tube pump was started after one day to obtain a good mixing in the melted salt and avoid sediments of undissolved salt hydrates.

After the salt was melted the heating was turned off and the salt slowly cooled down to room temperature. The salt showed only little supercooling and solidified without any external impact. Previous small scale tests have proven that the water content is very important for the supercooling and the water content should be a little higher than 40% to get a stable supercooling. Additional water was added and the experiment was repeated. In this experiment the salt supercooled as a jelly like substance.

The conclusions from this set of experiments are that it is possible to supercool large volumes of sodium acetate trihydrate, but the water content is of utmost importance, which means that a loss of water in the system should be avoided.

2.1.3.2 Filling of plastic laminate bags with fluid sodium acetate trihydrate

Experiments have been carried out with filling of laminated plastic bags with melted sodium acetate trihydrate both as warm salt (80 °C) and as supercooled salt at room temperature. The experiments with warm melted salt solution worked well, while the experiments with the supercooled salt solution failed due to immediate solidification when the supercooled salt was exposed to the surrounding air.

The experiments showed another benefit of the laminated plastic bag solution as the plastic bags when empty only contain a very small air volume, which means that the evaporation of water from the melted salt solution is very limited. Filling the bags in a vertical position (the opening facing upwards) allows the air in the bags to disappear during filling with sodium acetate trihydrate solution and the bags can be totally filled.

The conclusions from the filling experiments are that it is possible to fill the bags with warm melted sodium acetate trihydrate. It might also be possible to fill the bags with supercooled salt solution, but in this case the filling system should be sealed to avoid any water evaporation

2.1.3.3 Automated activation of supercooled salt

Activation of the solidification of the supercooled sodium acetate trihydrate by a microprocessor controller is a must if the concept should be feasible. Several different experiments of ways to activate the solidification of a supercooled salt solution have been tried out, e.g. ultrasound, local heating and mechanical by a piston injected into the salt by an electromagnet. The latter seems to be the most feasible solution resulting in activation of the solidification. The reason could either be the mechanical impact itself or the fact that the piston when withdrawn from the salt solution will hold some crystals that are injected next time the piston is activated. Figure 2.1.7 shows the tested piston and electromagnet solution for the automated activation.

Figure 2.1.7 Test of piston and electromagnet solution for automated activation.

2.1.3.4 Design specification and test results for prototype storage

The prototype storage described above is a very small test prototype storage, which is just large enough to investigate the control system, activation mechanism and the supercooling and to get an idea of the heat transfer possibilities. The prototype design is not at all optimised for maximum storage capacity per volume unit and therefore the figures in Table 2.1.1 are not at all representative for the expected final storage design.

Table 2.1.1 Design specification and test results for test prototype heat storage with Sodium acetate trihydrate.

Parameter	Measured Performance	Boundary Conditions
Storage materials weight: Sodium acetate trihydrate	kg	60
Storage capacity for heat	kWh	
Floor space required for prototype	m^2	1.3
Energy density of material (NRJ4.1) (ratio to water 35/70°C)	kWh/m^3 ( )	128 (3.2)
Energy density of prototype (NRJ4.2) (ratio to water 35/70°C)	kWh/m^3 ( )	10.9 (0.3)
Charge rate	kW	N/A
Discharge rate	kW	N/A
Estimated size for 70 kWh (energy density ratio to water 35/70°C)	m^3 ( )	2.8 (0.62)
Estimated size for 1000 kWh (energy density ratio to water 35/70°C)[1]	m^3 ( )	17 (1.4)

[1] Assumptions: storage made of 0.03 m thick plastic bags stacked on top of each other – each second bag filled with sodium acetate trihydrate. The total storage height has a maximum of 2.1 m, volume obtained by fitting the outer horizontal dimensions of the storage

2.1.4 Development Status

The initial experiments on how to work with the sodium acetate trihydrate and how to control the supercooling and the activation of the solidification have been carried out. The next steps are to finalize the test prototype and show the ability to control the storage and to measure the heat transfer to and from the salt hydrate with the present design. Based on the results from these experiments larger and more realistic prototype designs will be developed and experimentally tested.

A control unit for charge control of up to 4 separate subsections according to the control concept described in section 2.1.2.1 has been built.

2.1.5 Acknowledgements

The project is financed by the Danish Energy Authority.
The charge control unit has been sponsored by AllSun A/S.

2.1.6 References

[1] Furbo, S., Svendsen, S., Report on heat storage in a solar heating system using salt hydrates. Report no. 70, Thermal Insulation Laboratory, Technical University of Denmark, 1977.

[2] Schultz, J.M., Furbo, S., Investigation of heat of fusion storage for solar low energy buildings. Proceedings, ISES 2005 Solar World Congress, Florida, USA, 2005.

[3] Schultz, J.M., Furbo, S., Heat of Fusion Storage with High Solar Fraction for Solar Low Energy Buildings. Proceedings, Eurosun 2006, Glasgow, UK, 2006.

2.2 State of development of the work with PCM modules in DHW tanks at the University of Lleida

Luisa F. Cabeza, Cristian Solé, Research Group on Applied Energy, UdL

2.2.1 Background

The idea studied here was to add a PCM (Phase Change Material) module at the top of a hot water storage tank with stratification. The advantages of the stratification still remain in this new system, but the addition of a PCM module would give higher density in the top layer (Figure 2.2.1). One of the main advantages of this type of heat stores is the good use of low temperature heat and/or waste heat.

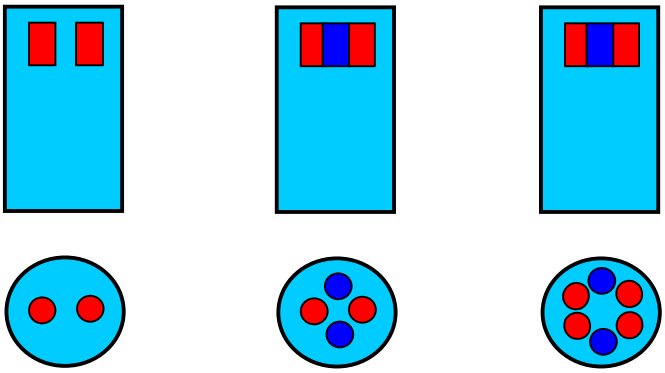

Figure 2.2.1 Configurations employed for experimental testing.

This idea is not new and its good performance was demonstrated in a previous paper. The work presented here is the inclusion of such a water tank with a PCM module in a complete pilot plant solar system. In this study, the performance of the water tank with different amounts of PCM is presented. This performance was evaluated in different test trials simulating different operation conditions. In a later work, the modelization of such a system with TRNSYS was also carried out.

2.2.2 Design and Operating Principles

To test the use of the PCMs in a real system, an experimental solar stand was constructed at the University of Lleida with such a goal. Figure 2.2.2 and Figure 2.2.3 show pictures of the installation. The stand had two thermal solar collectors, two hot water tanks of 146 L and an electrical heater outside the tanks, which allowed electrical heating with a known power when needed. The two water tanks were identical, but one had been modified to insert the PCM module. The right tank was equipped with thermocouples as indicated in Figure 2.2.3 to measure the temperature in the water at different levels. This allowed checking whether the water in the tank is still stratified. The thermocouples were fixed to the vertical pipe that extends over most of the tank interior and acts as cold water inlet.

Fig. 2.2.2 Solar thermal collectors from Takama.

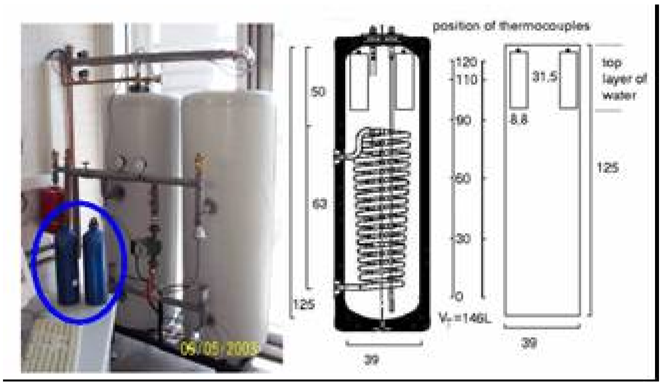

Fig.2.2.3 Hot water tanks from Lapesa and PCM modules.

The pilot plant could work continuously with the solar system, knowing that the primary pump operates when the water temperature of the tank is lower than the temperature from the collectors. On the other hand, the system could work occasionally with the electrical heater.

In previous papers the correct geometry of the PCM module and its influence on the performance of the water tank was studied. From the results of these simulations, the solution adopted was to use several cylinders at the top of the water tank instead of only one as shown in Fig 2.2.1. The modules used were commercial aluminium bottles filled with almost identical amounts of the PCM-graphite composite material.

A granular PCM-graphite compound of about 90 vol.% of sodium acetate trihydrate and 10 vol.% graphite was chosen as a phase change material. The data of the PCM graphite compound was given by the manufacturers with density of 1.35 – 1.4 kg/L, a melting point of 58ºC, a heat capacity of 2.5 kJ/kg·K, an enthalpy of 180 – 200 kJ/kg, and a thermal conductivity of 2 – 5W/m·K. The melting point and the enthalpy were tested in our laboratory with a Mettler Toledo DSC 822^e.

A set of experiments was carried out, with experiments classified as cooling down, discharging, charging and cycling tests. As a difference to the tests made before, these were done with four modules in the tank. The tests were realized twice due to the use of two different PCMs, sodium acetate trihydrate with/without graphite. As a reference, experiments with only water in the tanks were also done.

The cooling down tests were done heating up the tank until 70ºC and leaving it to cool down due to heat losses to the ambient.

In the discharge test, the water is heated until 70ºC, and then a cold flow rate of 300 L/h is pumped into the tank, until all temperatures in the tank are down at 20°C. This experiment was repeated with a flow rate of 600 L/h.

The charging experiment is started with the water tank at 20ºC, and a 600L/h flow of water at 70ºC is added until all the temperatures in the tank are hot.

Finally, the cycling consists in adding a 600 L/h cold flow rate during 5 minutes, starting at 70ºC. Then stop the flow rate for 10 minutes, and afterwards add the same cold flow rate until all the temperatures are equalized.

2.2.3 Laboratory Test Results

Figures 2.2.4 – 2.2.7 show the results from the laboratory tests performed in Lleida.

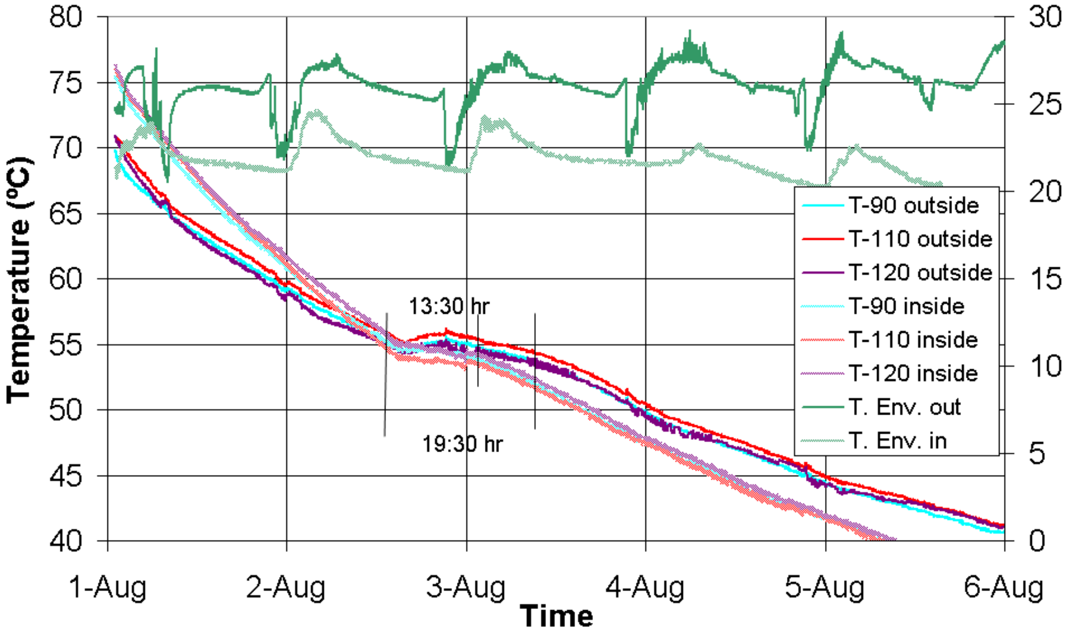

Figure 2.2.4 Cooling down experiments with sodium acetate trihydrate with graphite.

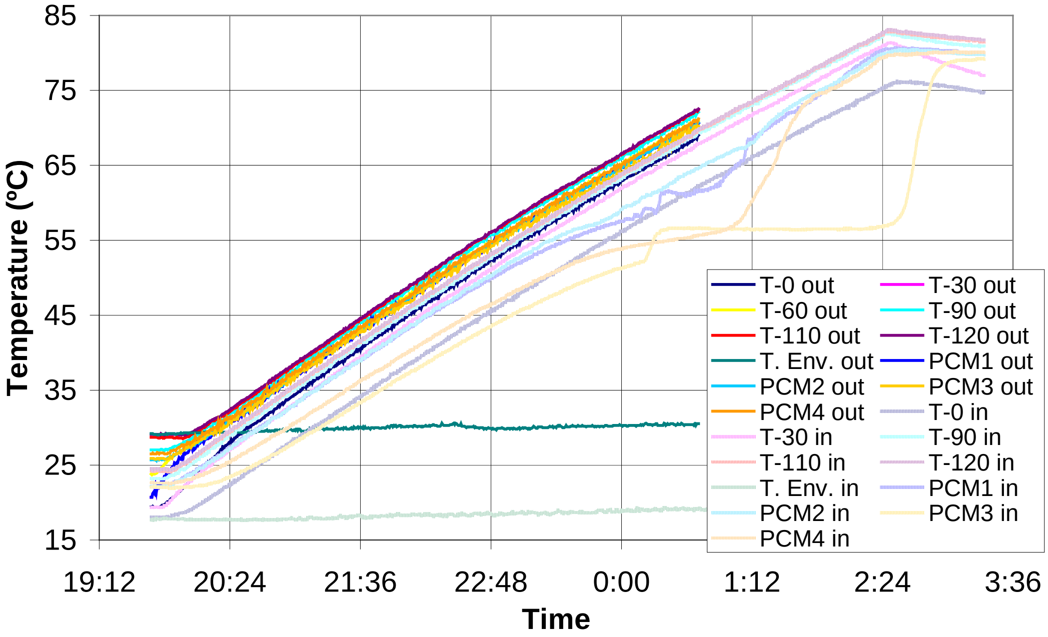

Figure 2.2.5 Charge experiments with sodium acetate trihydrate with graphite.

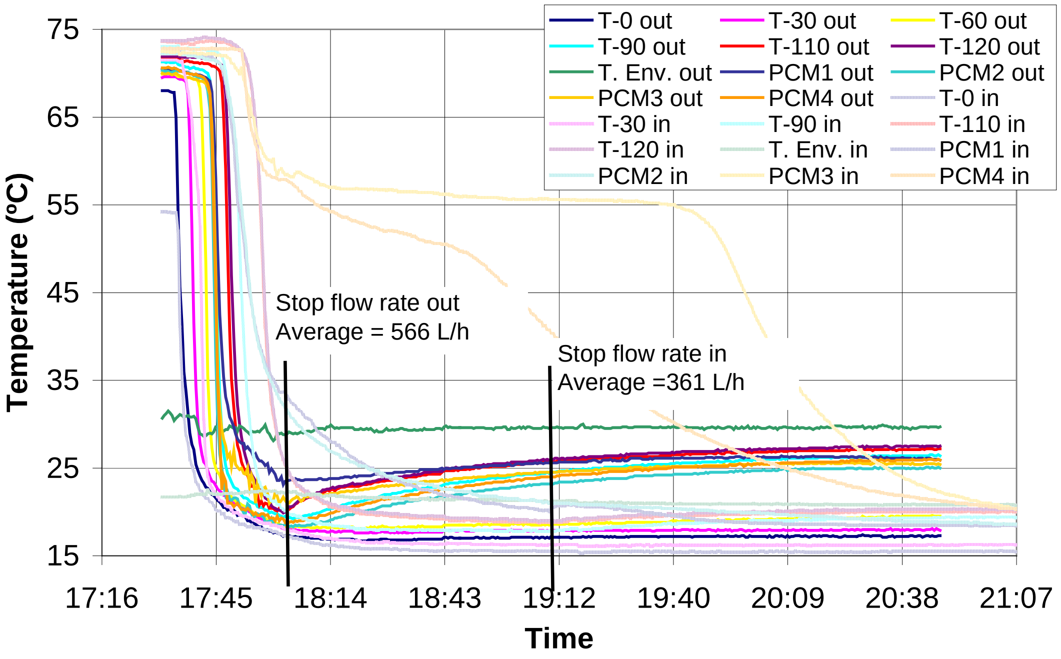

Figure 2.2.6 Discharge experiments with sodium acetate trihydrate and graphite.

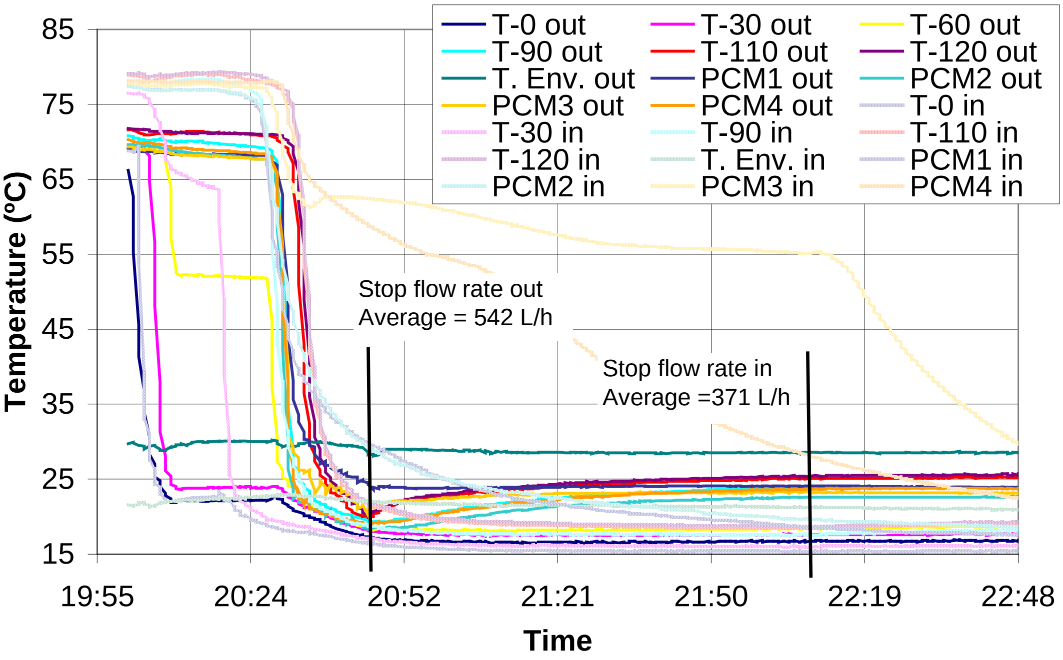

Figure 2.2.7 Results from cycling experiments with sodium acetate trihydrate and graphite.

Table 2.2.1 Design specification and test results for a PCM-water tank with 4 PCM modules inside.

Parameter	Measured Performance	Boundary Conditions
Storage materials weight: Material 1 Material 2	 kg kg	 Water 140 Sodium acetate trihydrate graphite 4.2
Storage capacity for heat	kWh	
Floor space required for prototype	m^2	0.25
Energy density of material (NRJ4.1) (ratio to water 20/70°C)	kWh/m^3 ( )	Water 58 (1) Sodium acetate trihydrate with graphite 56 (0.97)
Energy density of prototype (NRJ4.2) (ratio to water 20/70°C)	kWh/m^3 ( )	58 (1)
Charge rate	kW	
Discharge rate	kW	
Estimated size for 70 kWh (energy density ratio to water 20/70°C)	m^3 ( )	1.2 (1)
Estimated size for 1000 kWh (energy density ratio to water 20/70°C)[1]	m^3 ( )	17.2 (1)

[1] Assumptions: 146 l tank volume: 140 l water + 6 l PCM
4,2 kg of PCM

The main conclusions from the experiments are:

1. Cooling down experiments
   - Sodium acetate trihydrate cools down slower than sodium acetate trihydrate + graphite due to its worse heat transfer
   - There is a big dependence from the ambient temperature in long term storage (i.e. cool down test)
2. Charging experiments
   - When only sodium acetate trihydrate is used, the PCM temperature is the same as the water temperature, no melting is appreciate in Figure 2.2.5
   - On the other hand, a clear melting process is observed when using graphite mixed with the sodium acetate trihydrate
3. Discharging experiments
   - All at 20ºC → water or PCM?
     - If high flow rate → PCM is not fully solidified and a reheating process is observed
     - If low flow rate → No reheating is observed, PCM is fully solidified
   - There was no influence of the ambient temperature due to the short time of the test, therefore comparison of the graphics was possible
4. Cycles experiments
   - The five-minutes shower does only affected the bottom of the tank

2.2.4 Development Status

A combisystem prototype will be set up and tested at the University of Lleida. The combistore will have a capacity of 605 L, 180 L for the DHW and 425 for the heating. PCM modules will be placed in the upper part of the tank as it was done in the DHW tanks before. Some PCM modules will be set inside the DHW tank as it is shown in Fig. 2.2.8.and some more in the tank used for the heating but also in the upper part. Therefore the effect of the PCM will be used to heat up the water of the DHW volume.

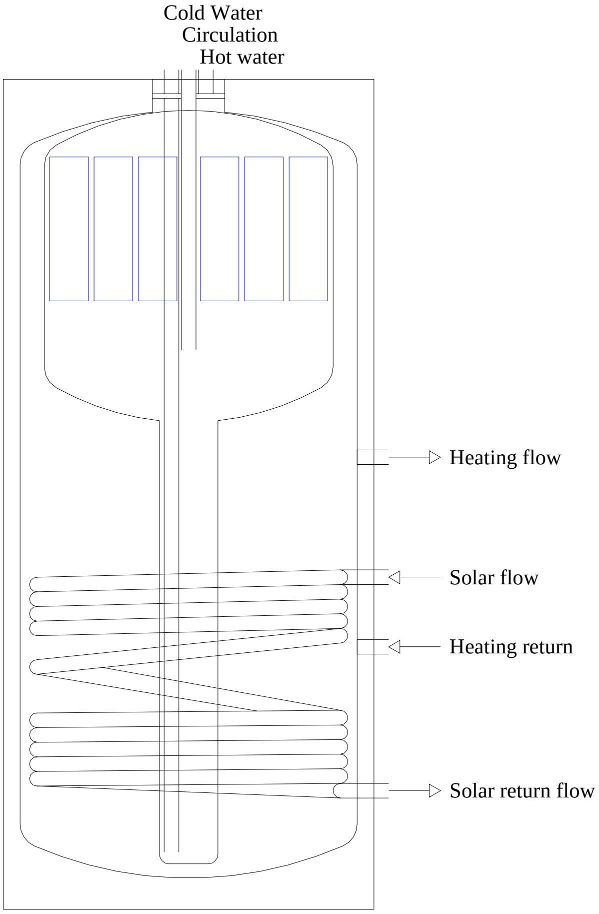

Figure 2.2.8 Combistore prototype design.

2.2.5 References

Mehling, H., Cabeza, L.F., Hippeli, S., Hiebler, S., PCM-module to improve hot water heat stores with stratification. Renewable Energy 28 (2003) 699-711.

[1] Nogués, M., Cabeza, L.F., Roca, J. Illa, J., Zalba, B., Marín, J.M., Hiebler, S., Mehling, H., Efecto de la Inserción de un Módulo de PCM en un Depósito de ACS. Anales de la Ingenieria Mecánica, vol 1 (2002) 398-402.

[2] Cabeza, L.F., Ibáñez, M., Solé, C., Roca, J., Nogués, M., Experimentation with a water tank including a PCM module. Solar Energy Materials and Solar Cells, 90 (2006), 1273-1282.

[3] Ibáñez, M., Cabeza, L.F., Solé, C., Roca, J., Nogués, M., Modelization of a water tank including a PCM module. Applied Thermal Engineering, 26 (2006), 1328-1333.
[4] Mazman, M., Cabeza, L.F., Mehling, H., Evliya, H., Paksoy, H.O., Günes Enerjisiyle su Isitma Sistemlerinde Faz Degistiren Madde Kullanimi, in: Proceedings at UTES 2004, Istanbul, Turkey (2004).
[5] Cabeza, L.F., Mehling, H., Hiebler, S., Ziegler, F., Heat transfer enhancement in water when used as PCM in thermal energy storage. Applied Thermal Engineering 22 (2002) 375-380.

2.3 State of development of work with PCM stores at the Institute of thermal Engineering, University of Applied Sciences of Western Switzerland

Bony, J. & Citherlet, S. HES-SO / IGT / LESBAT

2.3.1 Background

The first developments of the test bench at the HES-SO occurred during the IEA-SHC Task 26. It is based on the commercialised combisystem Arpege from the Swiss company Agena.

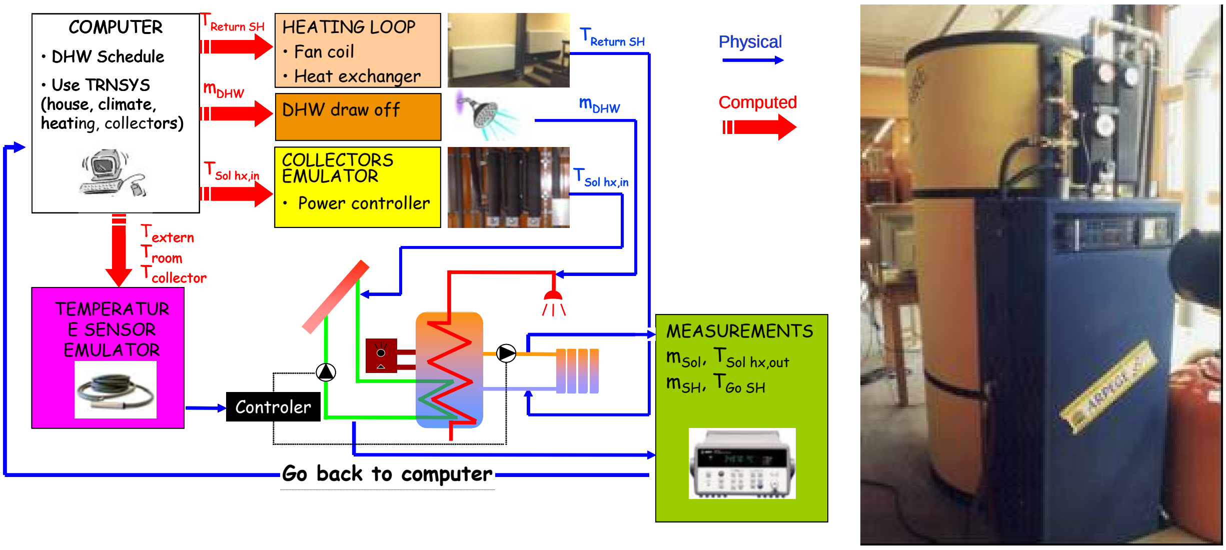

Figure 2.3.1 Principle diagram of test bench and combisystem Arpege.

In the test bench the solar collectors are emulated (hybrid simulation) by an electric heating system on the solar circuit which is controlled by the software LabVIEW using a setup temperature simulated by TRNSYS. The heat from the building heating loop is rejected with a fan coil unit and a water heat exchanger if the fan coil is insufficient. The DHW demand is extracted periodically according to a profile that can be defined.

2.3.2 Design and Operating Principles

The Arpege system is made of a 824 l water tank with two heat exchangers, one for the solar loop (bottom) and the second for the DHW (bottom to top). The auxiliary-heat system is a gas burner with an efficiency of 98% (low calorific value) placed at mid height in the tank as shown in the Figure 2.3.2.

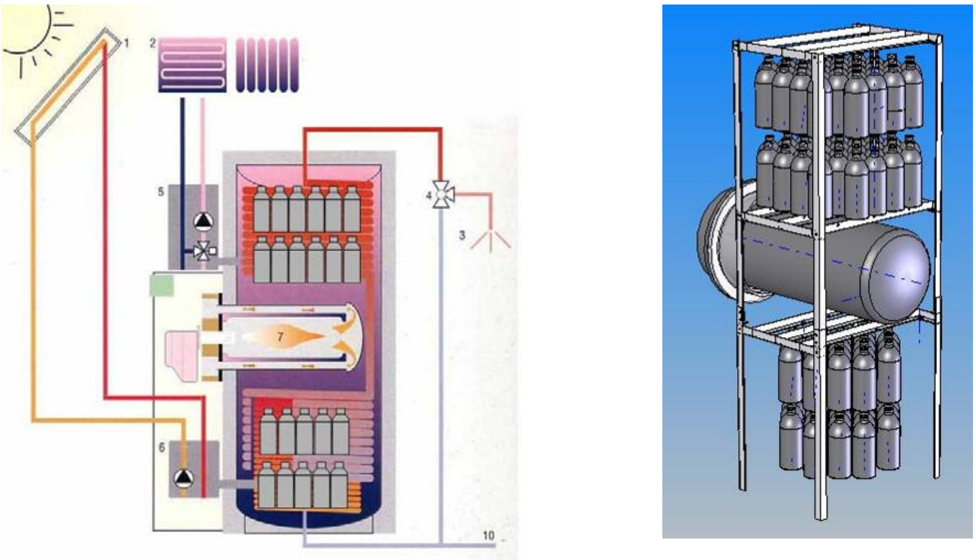

Figure 2.3.2 Arpege drawing with PCM bottles.

In this project, PCM bottles of about 1l volume will be placed in the water tank. The bottles are made of aluminium and the caps are made of polypropylene. The latter have been modified in order to resist pressure variation between the water tank and the PCM in the bottle. The modification consists in an aluminium disk and a rubber disk. The system has been tested in a special tank in which the pressure could be modified. The bottle has resisted to a relative pressure between minus one bar to three bars.

2.3.3 Laboratory Test Results

We have updated the Arpege test bench in order to measure the performances of the Arpege combisystem with PCM. Several tests have been performed to evaluate the reproducibility of the measured data over a period of one week. Currently, the tested system does not include the PCM, but has shown a good reproducibility between two sets of measurements. The measurement has also shown a good agreement compared to simulation results obtained with TRNSYS, as shown in Figure 2.3.3

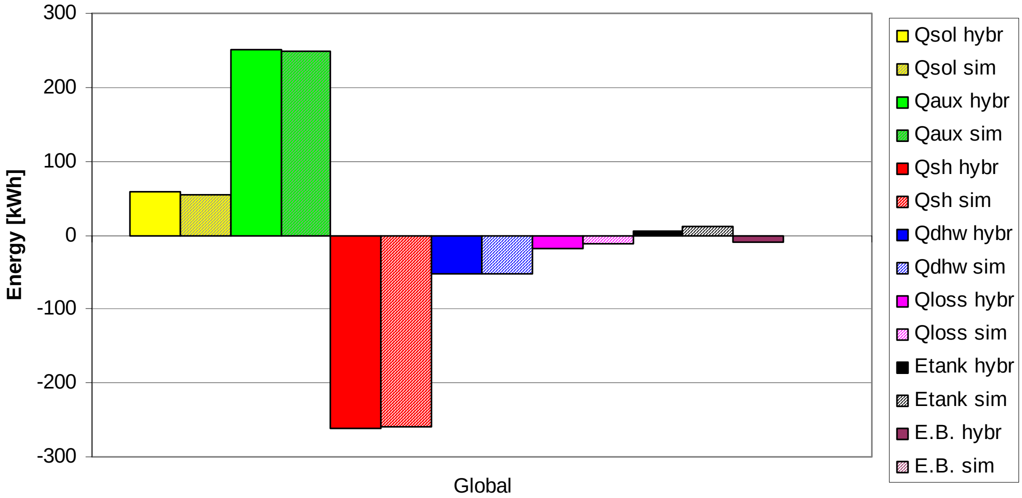

Figure 2.3.3 Comparison of measurements and TRNSYS simulations. Yellow=solar; Green=auxiliary; Red=heating demand; Blue=DHW; Pink=thermal losses from tank; Black=internal energy tank; Brown=energy balance

Table 2.3.1 Design specification and test results for the Arpege system.

Parameter	**Measured Performance**	**Boundary Conditions**
Storage materials weight: Water Sodium acetate trihydrate Paraffin RT27	kg kg kg	710 90 43
Storage capacity for heat	kWh	
Floor space required for prototype	m^2	1.8 m^2
Energy density of material (NRJ4.1) (ratio to water 25/85°C)	kWh/m^3 ( )	Water 69,7 Sodium acetate trihydrate 81.2 (1.16) Paraffin RT27 58.3 (0.84)
Energy density of material (ratio to water 15/35°C)[a]	kWh/m^3 ( )	Water 23.2 Sodium acetate trihydrate - Paraffin RT27 57 (2.45)
Energy density of material (ratio to water 50/70°C)[a]	kWh/m^3 ( )	Water 23.2 Sodium acetate trihydrate 51.4 (2.21) Paraffin RT27 -
Energy density of prototype (NRJ4.2) (ratio to water 25/85°C)	kWh/m^3 ( )	70 (1.0)
Charge rate	kW	Auxiliary 20 kW
Discharge rate	kW	DHW around 30 kW
Estimated size for 70 kWh (energy density ratio to water 25/85°C)	m^3 ( )	1 (1)
Estimated size for 1000 kWh (energy density ratio to water 25/85°C)[1]	m^3 ( )	14.3 (1)

a) Due to the temperature frequency the temperature range used in the lower part of the tank is 15 to 35 [°C] and in the upper part is 50 to 70 [°C] as shown Figure 2.3.4.

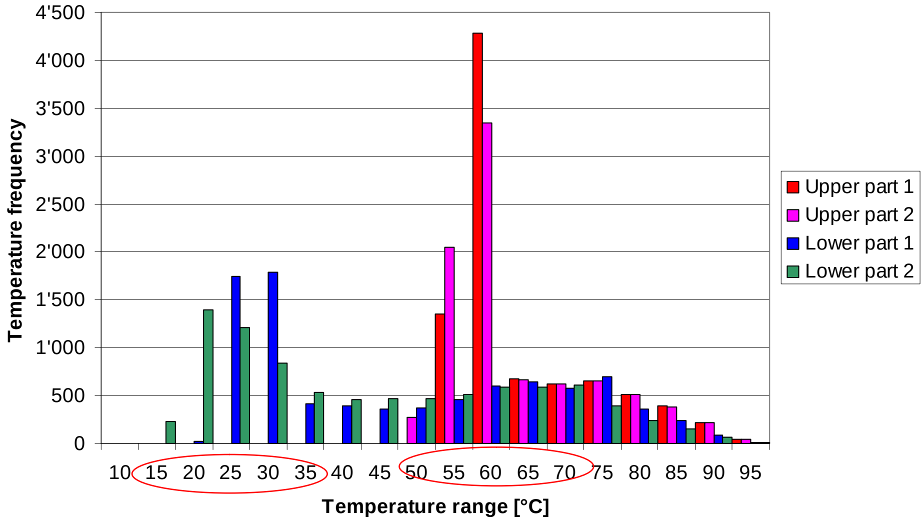

Figure 2.3.4 Temperature frequency according to the height level storage.

2.3.4 Development Status

1) Combisystem performance

A set of 106 bottles filled with paraffin (40%) and sodium acetate trihydrate (60%) is ready to be plunged in the water tank. The occupied volume will represent approximately 15% percent of the tank volume, as show in Figure 2.3.2

This low ratio of PCM is due to various problems:

- The two heat exchangers
- The extra-heating system
- The bottles are not filled to the top to allow for PCM expansion.

Nevertheless, these tests with a rather low PCM ratio will be undertaken. The results will then be compared to the simulation results, in order to validate the model developed for TRNSYS.

2) High PCM Ratio

Increasing the PCM ratio is not possible in the Arpege test bench. Therefore, we will test a higher ratio, about 30%, in another water tank, as shown in Figure 2.3.5. This second set of experimental data, will be helpful to compare the results obtained with our simulation model.

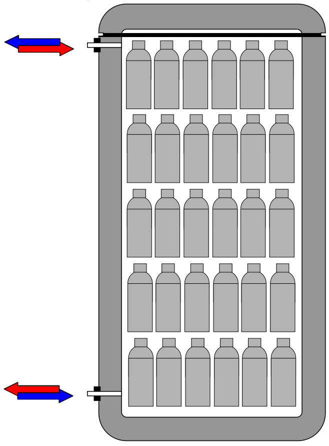

Figure 2.3.5 Water tank fill with PCM bottle

3) LCIA

The life-cycle impact analysis has been calculated for the Arpege system. It includes all elements of the commercialised system plus the PCM storage, which is made of the paraffin, the aluminium bottles and the polypropylene caps. The PCM can account for about 30% of the combisystem and 20% of the GWP impacts, as shown in the Figure 2.3.6.

When we also take into account of the extra-energy demand over a 20 years service life, the PCM storage accounts between 1 and 5% of the total impacts (materials + energy), depending on the extra-heating energy vector used, as shown in the Figure 2.3.7.

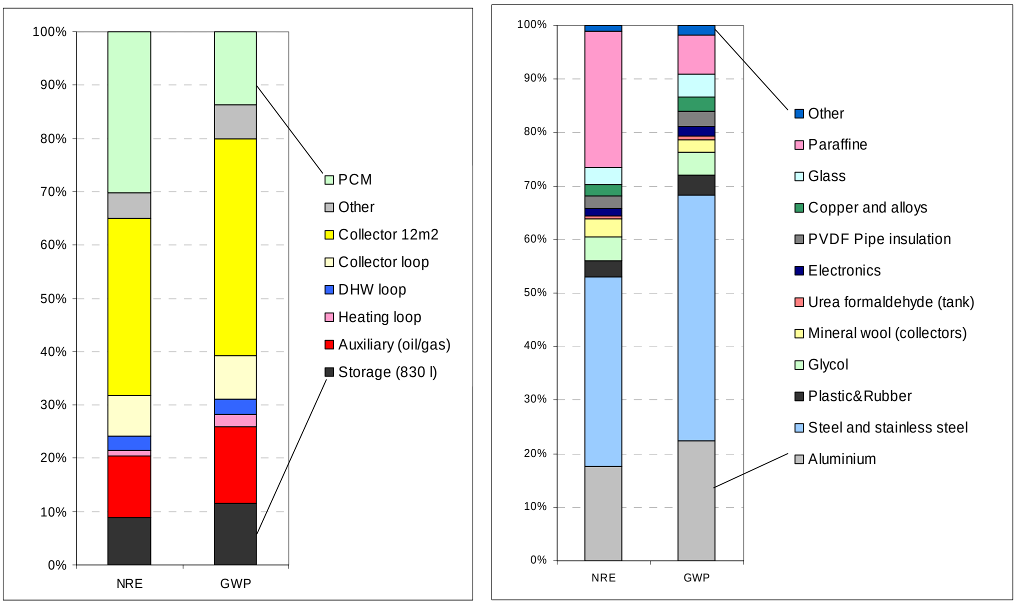

Figure 2.3.6 LCIA of the Arpege system by elements (left) and by materials (right)

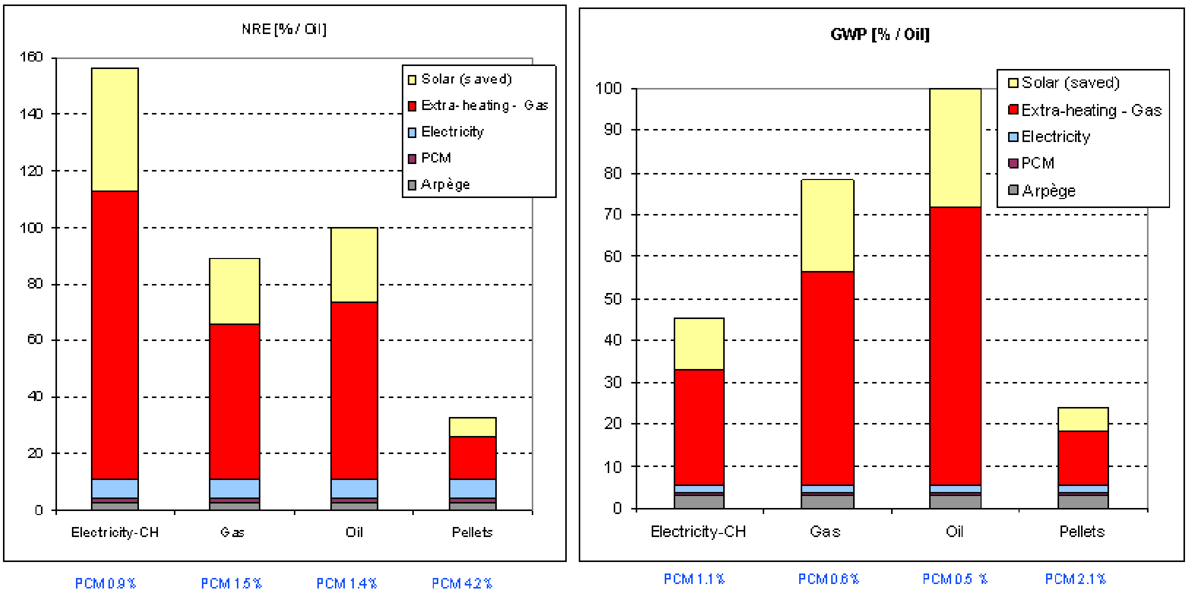

Figure 2.3.7 LCIA of the Arpege system for different energy heating vectors.

When the performances of the Arpege system with PCM will be available, the energy demand in the LCIA analysis will be updated. The analysis could also be extended for other countries with different electricity mixes.

3) Sodium acetate trihydrate

It seems that the durability of the sodium acetate trihydrate is not known, when subject to several thousands of thermal cycles. We would like to develop a test bench to evaluate the evolution of these PCM performances after 20’000 cycles which may occur during a 10 to 20 year life span. This will be performed by charging and discharging a water tank containing several samples of the sodium acetate trihydrate. The PCM performance will be measured before and after the test.

4) Other systems

When the simulation model will be validated with experimental data, different configurations will be simulated (climate, PCM ratio, PCM parameters, etc.). Some other systems (Heat exchanger position, water tank volume and numbers, etc.) will also be simulated to evaluate the potential of the PCM for different types of solar systems.

2.3.5 Acknowledgements

We would like to thank our national government: Federal Office of Energy (OFEN/BFE).

We also would like to deeply thank Jean-Christophe Hadorn, representative of the International Energy Agency (IEA) for having initiated the IEA-SHC Task 32.

2.3.6 References

[1] Bony, J., et al., *Three different approaches to simulate PCM bulk elements in solar storage tank*, PCM2005, Yverdon-les-Bains, June 2005.

[2] Bony, J., and Citherlet, S., Extesion of a TRNSYS model for latent heat storage with phase change materials used in solar water tank, Ecostock2006, Stockton.

2.4 State of development of work with PCM stores at the Institute of thermal Engineering, Graz University of Technology

Andreas Heinz, TU Graz. Institute of Thermal Engineering

2.4.1 Background

At the Institute of Thermal Engineering, Graz University of Technology, different approaches of integrating PCMs into thermal storage tanks are studied:

- macro-encapsulation
- PCM tank with an immersed heat exchanger
- microencapsulated PCM slurry

4 different experimental tanks have been built and tested in the laboratory. The goal of the work is to find a simple and efficient way of PCM integration, that allows both high energy densities and high charge and discharge powers. Besides a measurement method for the enthalpy as a function of temperature was applied and further developed.
The results of the experimental work are also used to validate a PCM storage simulation model that has been developed at the Institute [1].

2.4.2 Design and Operating Principles

2.4.2.1 Macroencapsulation

Different types of PCMs were encapsulated in modules of cylindrical shape which were integrated into a water tank with a volume of 34 litres (Figure 2.4.1). This tank is used to analyze the heat transfer processes between the PCM and the surrounding water (convection), the heat conduction inside of the PCM modules and the storage capacity of different PCMs. Additionally the experimental data is used to validate simulation models for storage tanks with integrated PCM modules, that are developed in the framework of the IEA SHC TASK 32 [2].

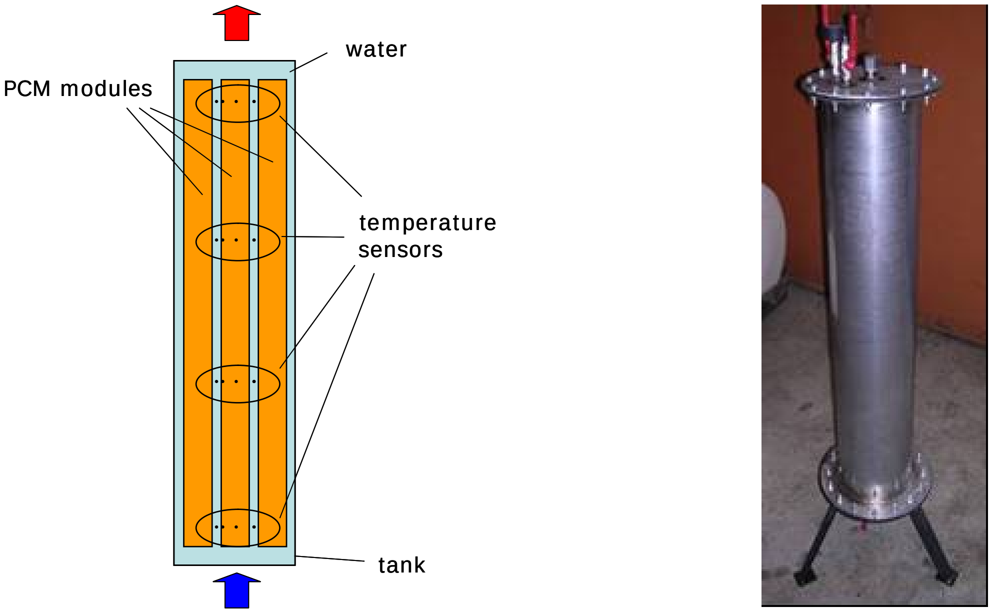

Figure 2.4.1. Schematic and photo of the PCM store with cylindrical modules.

2.4.2.2 PCM storage with immersed heat exchanger

Another approach studied is to fill a tank directly with the PCM and to charge and discharge it with a suitable heat exchanger. For the heat transfer between the heat carrier fluid and the PCM an air-to-water heat exchanger is used (Figure 2.4.2). The used heat exchanger has a large number of thin fins, that extend the heat exchanger surface, usually on the air side of a liquid-to-air heat exchanger, but in this case the fins are used to enhance the heat transfer in the PCM. With this type of store high volume fractions of the PCM are possible and the heat exchanger allows high charge and discharge powers.

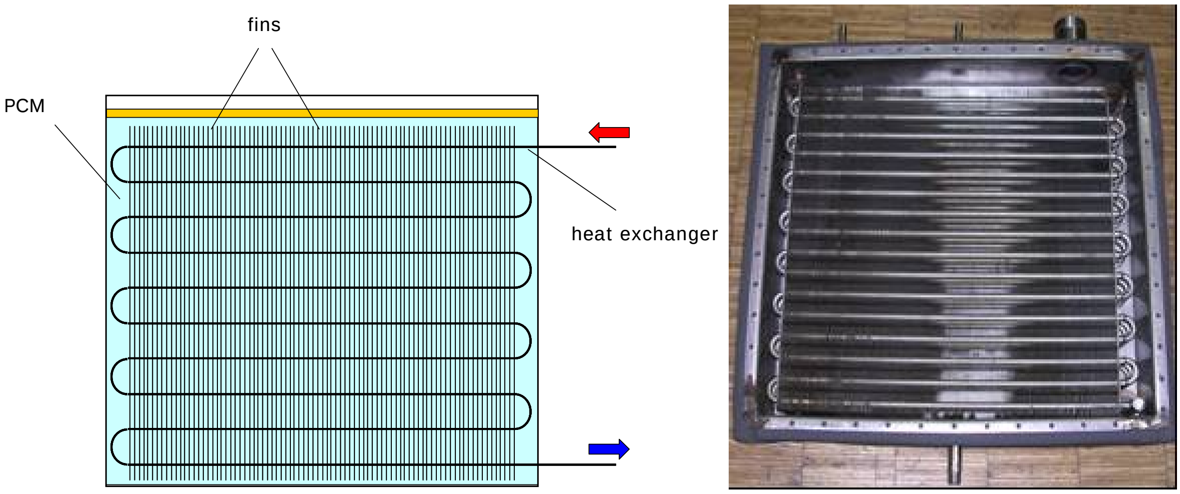

Figure 2.4.2 schematic and photo of the PCM store with immersed heat exchanger.

2.4.2.3 Microencapsulated PCM slurries

Paraffins can also be microencapsulated with diameters of just a few µm. Due to the small diameter the ratio of surface area to volume is very high and the low thermal conductivity is not a problem. If these microcapsules are dispersed in a fluid (mostly water), they form a pumpable slurry, that can be used as an energy transport- and storage medium, a so-called PCM slurry.

At the Institute of Thermal Engineering two storage tanks filled with a PCM slurry from BASF with a melting point at about 60°C have been tested. One of the tanks is charged/discharged with a spiral type internal heat exchanger like it is commonly used in hot water and buffer store tanks (Figure 2.4.3). The second tank was directly charged/discharged via a double port and an external flat plate heat exchanger. The heat transfer was analysed for different concentrations of microcapsules in the slurry with the internal and the external heat exchanger [3].

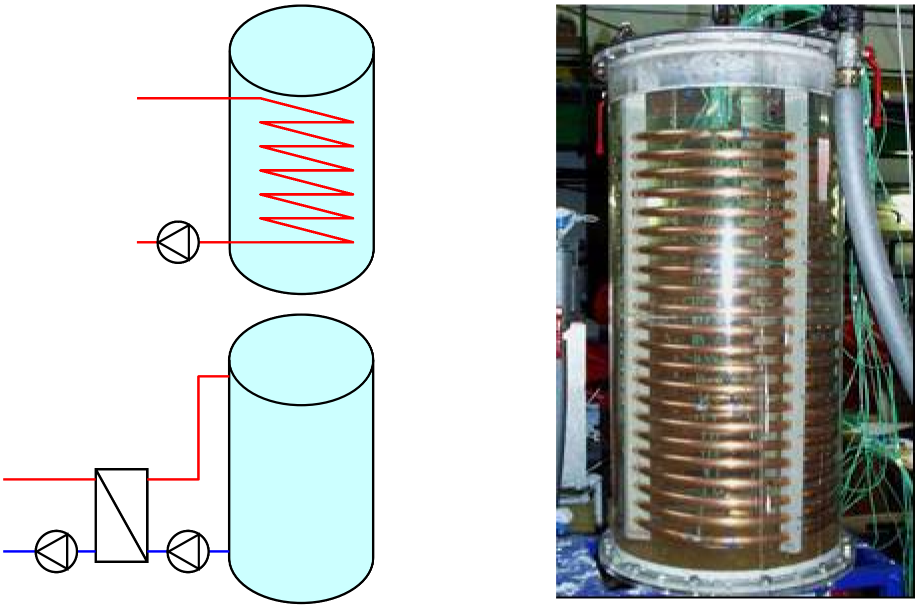

Figure 2.4.3 schematic of the PCM slurry stores (top: internal heat exchanger, bottom: external heat exchanger), photo of the PCM slurry store with internal heat exchanger (here filled with water).

2.4.3 Laboratory Test Results

2.4.3.1 Storage tank with macro-encapsulated PCM

The evolution of the discharge power with time for different PCM materials inside of the cylindrical PCM modules was measured (see Figure 2.4.4). At the beginning of the experiment the discharge powers are relatively high, which is a result of the hot water being pushed out of the tank by the cold water entering at the bottom. After that the heat is discharged only from the PCM modules. With the paraffin as well as with sodium acetate trihydrate the discharge power is quite low, due to the low thermal conductivity of these materials. This results in a very long discharge time and a limitation concerning the possible applications. When the sodium acetate trihydrate graphite compound is used inside the modules, the achievable discharge power is much higher, due to the enhancement of the thermal conductivity. In the graphs of the measurements with sodium acetate trihydrate (with and without graphite) a subcooling effect can be observed, resulting in a local minimum of the discharge power.

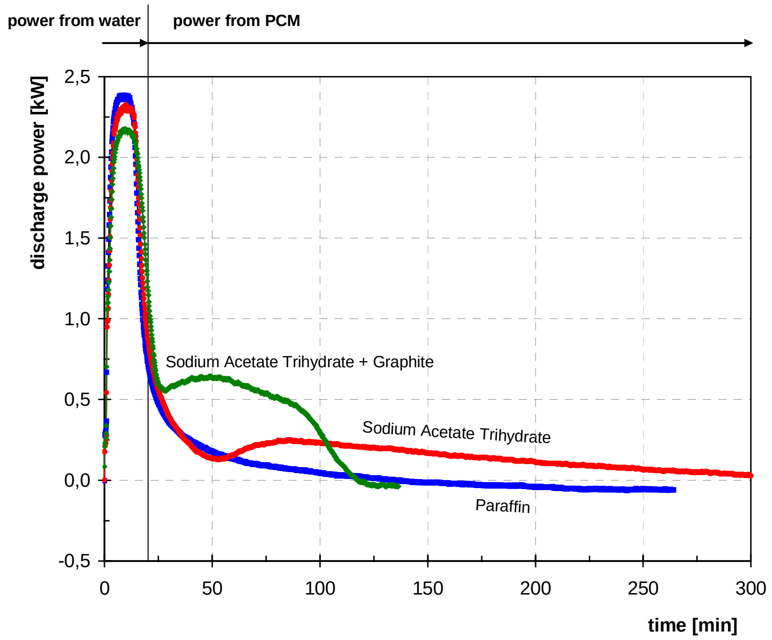

Figure 2.4.4 Discharge power with different PCM materials for a cooling experiment, mass flow 100 kg/h, flow temperature 50 °C, start temperature of the tank 70 °C.

Table 2.4.1 Design specification and test results for modules with Sodium acetate trihydrate +Graphite.

Parameter	**Measured Performance**	**Boundary Conditions**
Storage materials weight: Sodium acetate trihydrate+Graphite Water	 kg kg	 13.7 20.8
Storage capacity for heat	kWh	
Floor space required for prototype	m^2	0,4
Energy density of material (NRJ4.1) (ratio to water 50/70°C)	kWh/m^3 ( )	85 (3.7)
Energy density of prototype (NRJ4.2) (ratio to water 50/70°C)	kWh/m^3 ( )	40 (1.7)
Charge rate	kW	0.5-1
Discharge rate	kW	0.5-1
Estimated size for 70 kWh (energy density ratio to water 50/70°C)	m^3 ( )	1.75 (1.7)
Estimated size for 1000 kWh (energy density ratio to water 50/70°C)[1]	m^3 ( )	25 (1.78)

[1] Assumptions: total storage volume: 34 litres
PCM volume fraction: 30%
Sodium Acetate Trihydrate + graphite as PCM

2.4.3.2 PCM storage with immersed heat exchanger

As an example Figure 2.4.5 shows a discharging experiment performed with the PCM storage with immersed heat exchanger. The tank is filled with Sodium acetate trihydrate as PCM, with a volume fraction of about 80 %. Due to the high heat exchanger area the achieved discharge power is approximately 17 kW with an outlet temperature of 50°C during the phase change of the PCM.

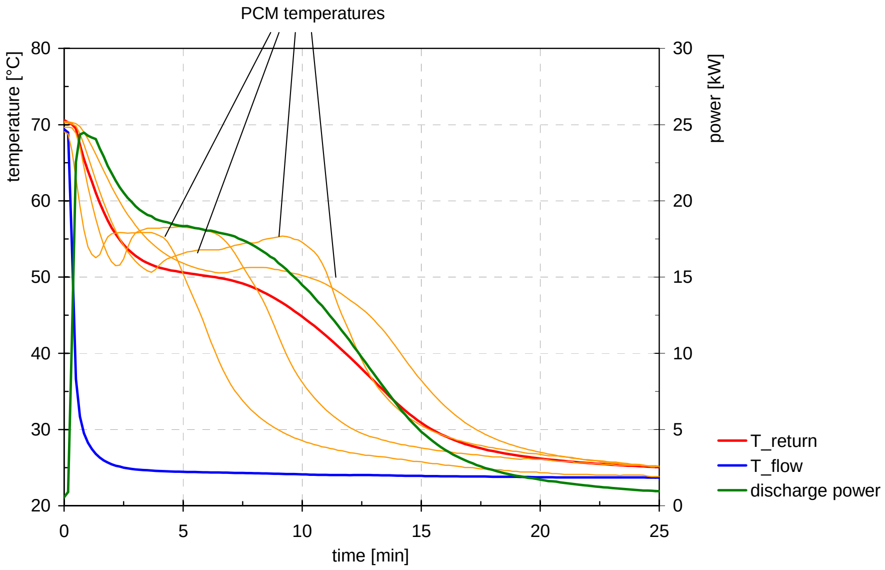

Figure 2.4.5 Discharge power for a cooling experiment, mass flow 600 kg/h, flow temperature 25 °C, start temperature of the tank 70 °C

Table 2.4.2 Design specification and test results for store with Sodium Acetate Trihydrate

Parameter	Measured Performance	Boundary Conditions
Storage materials weight: Sodium acetate trihydrate Water	 kg kg	 45 0
Storage capacity for heat	kWh	
Floor space required for prototype	m^2	0,2
Energy density of material (NRJ4.1) (ratio to water 50/70°C)	kWh/m^3 ( )	103 (4.44)
Energy density of prototype (NRJ4.2) (ratio to water 50/70°C)	kWh/m^3 ( )	76 (3.3)
Charge rate	kW	5-20
Discharge rate	kW	5-20
Estimated size for 70 kWh (energy density ratio to water 50/70°C)	m^3 ( )	0.92 (3.0))
Estimated size for 1000 kWh (energy density ratio to water 50/70°C)[1]	m^3 ( )	13 (3.3)

[1] Assumptions: total storage volume: 45 litres
PCM volume fraction: 72%
Sodium acetate trihydrate as PCM

2.4.4 Development Status

Different approaches for using PCMs in thermal storage tanks have been analysed. The work with PCM slurries, manufactured by BASF, showed that this technology cannot be usefully applied for solar thermal systems yet, due to the relatively low latent energy and the therefore low improvement compared to conventional sensible heat storage in water. Additionally the so far used slurry had problems with separation and blocking of tubes without volume flow. This may be overcome by smaller sizes of the microcapsules.

PCM encapsulated in modules (macro-encapsulation) was tested with different materials for the PCM itself and the module envelope. The necessity of PCMs with high thermal conductivity and the size of the modules, that have to be used, depend on the desired application. As the simulation models developed in the framework of Task 32 have been validated by experimental data, simulations for different systems can be performed as a next step. All influencing parameters concerning the PCM tank, like thermal conductivity, module size, subcooling etc. can be considered and optimized for different applications.

The PCM tank with immersed heat exchanger allows high charge/discharge powers and high energy densities due to the high volume fraction of PCM. Problems that still need to be solved are the possible corrosion problems because of material combinations of the heat exchanger, and the question how to simultaneously charge and discharge the tank.

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We also want to thank the industrial partners “BASF” and “SGL Carbon” for their support and the supply with materials.

2.4.6 References

[1] Schranzhofer, H. Heinz, A. Puschnig, P., Streicher, W., (2006), Validation of a TRNSYS simulation model for PCM energy storages and PCM wall construction elements, Ecostock Conference, 31th May – 2nd June 2006, Pomona, USA

[2] Bony, J., et al., (2006), Three different approaches to simulate PCM bulk elements in solar storage tank, PCM2005, Yverdon-les-Bains, June 2005.

[3] Heinz, A., Streicher, W., (2005), Experimental testing of a storage tank filled with microencapsulated PCM slurries, Phase Change Material and Slurry: Scientific Conference and Business Forum, 15.-17. Juni 2005, Yverdon les Bains, Schweiz, S. 67 – 76

[4] Heinz, A. Streicher, W., (2006), Application of Phase Change Materials and PCM slurries for thermal energy storage, Ecostock Conference, 31th May – 2nd June 2006, Pomona, USA

3 COMPARISON OF PROTOTYPES

There are five PCM related projects included in Task 32:

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

- In Lleida University, Spain bottles of PCM material with graphite matrix for the enhancement of the heat conduction und increase of power input/output is tested. Applications are free-cooling and DHW tanks
- In the Applied University of West-Switzerland in Yverdon les Baines/Switzerland a parametric study for the use of PCM in heat stores for solar combisystems is carried out.
- The Institute of Thermal Engineering at Graz University of Technology performs 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

- In the Department of Civil Engineering, Technical University of Denmark, the use of super cooling of PCM materials for long-term heat storage is investigated with simulations and laboratory experiments.
- The Institute of Thermal Engineering at Graz University of Technology performs tests and simulations with PCM-slurries with microencapsulated paraffins for stores for conventional boilers to reduce the number of start-stop cycles. TRNSYS modules are developed 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 side.

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

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

The results of the systems are shown in Table 3.1

Table 3.1 Comparison of the stores with PCM material

Parameter	**DTU**	**Lleida**	**HEIG-VD**	**TU Graz**	**TU Graz**
Type of technology	Seasonal storage with subcooled	Macroencapsulated PCM in solar combistore	Macroencapsulated PCM in solar combistore	Macroencapsulated PCM in store for boiler	Immersed heat exchanger in PCM store
Cost of material					
Storage materials weight: in kg	$Na(CH_3COO)\cdot 3\ H_2O$: 60	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite: 4.2 Water: 140	$Na(CH_3COO)\cdot 3\ H_2O$ +graphite: 90 water: 30 paraffin RT27: 43	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite: 13.7 water :20.8	$Na(CH_3COO)\cdot 3\ H_2O$: 45 Water: 0
Temperature difference in tank	35/70°C	20/70°C	25/85	50/70°C	50/70°C
Floor space required for prototype	1.3 m^2	0.25 m^2	1.8 m^2	0.4 m^2	0.2 m^2
Energy density of material (NRJ4.1) in kWh/m³ (ratio to water)	128 (3.2)	56 0.97)	Water 69,7 SAT 81.2 (1.16) Paraffin RT27 58.3 (0.84)	85 (3.7)	103 4.44
Energy density of prototype - heat (NRJ4.2) in kWh/m³ (ratio to water)	10.9 (0.3)	57 (0.98)	70 (1.0)	40 (1.7)	76 3.3
Energy density of material in kWh/m³ (ratio to water, 15/35°C)			Water 23.2 Paraffin RT27 57 (2.45)		
Energy density of material in kWh/m³ (NRJ4.2) (ratio to water, 50/70°C)			Water 23.2 SAT 51.4 (2.21)		
Charge rate in kW	N/A		Auxiliary 20	0.5-1	5-20
Discharge rate in kW	N/A		DHW around 30	0.5-1	5-20
Estimated size for 70 kWh in m³ (energy density ratio to water)	2.8 (0.6)	1.2 (1)	1 (1)	1.75 (1.7)	0.92 (3.0)
Estimated size for 1000 kWh in m³ (energy density ratio to water)	17 (1.4)	17.5 (1)	14.3 (1)	25 (1.7)	13 (3.3)

SAT = sodium acetate trihydrate

4 Final conclusions

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 have 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. Whereas 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 effects 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 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 lower specific power. The projects are 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 immersed heat exchanger for the store of Institute of Thermal Engineering of Graz University of Technology can be sized about 1/3 of the volume compared to water by using sodium acetate trihydrate. With this layout additionally the about 20 kW thermal power can be delivered for the DHW production. For the same PCM-material but macro-encapsulated and for a temperature lift from 25 to 85 or 20 to 70°C in solar combisystems the store has the same size as a water store. For such cases, there is only little benefit from PCM with respect to store size.

For the seasonal storage of PCM the comparison to water stores is not as simple, because there are no heat losses of the subcooled PCM store. Compared to the theoretical heat storage of water without heat losses the PCM store can be reduce by about 30 %. Taking into account the long term heat losses of water stores the size reduction is far bigger.

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.

Phase change materials as heat storage 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. The other possible application is the use of the subcooling effect for seasonal storage. The investigations reported here showed only little advantages for macro-encapsulated PCM modules in combistores and for PCM slurries for heat stores in solar combisystems.