Laboratory Prototypes of PCM Storage Units

Improvements since Report C3 in May 2007

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

Advanced storage concepts for solar and low energy buildings

Report C4 of Subtask C

March 2008

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Task 32
Storage

SHC
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Project Report C4 of Subtask C

Laboratory Prototypes of PCM Storage Units

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by

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A technical report of Subtask C

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Executive Summary

In Report C4 additional analysis compared to Report C3 of the systems of Lleida University, Spain and University of Applied Sciences Western Switzerland in Yverdon-les-Bains/Switzerland (HEIG-VD) are presented

At Lleida University, Spain the same store with three different fillings has been studied:

- pure water,
- aluminium bottles filled with sodium acetate trihydrate with graphite and
- the coil of the heat exchanger in the middle of the tank with additional three bottles filled with sodium acetate trihydrate with graphite.

Discharge flow rates were performed. There was no significant increase of the energy content of the three tanks, but as the maximum theoretical increase was only 2 % this was expected. The main focus of theses experiments was laid on the level of stratification within the tanks. It could be shown, that the stratification was not disturbed by the (little amount) of PCM in the store.

At HEIG-VD a 7 days measurement for a heating period assuming a sunny winter period and a DHW test over 24 hours with a large and a small draw off were performed for a store with pure water and in comparison with a heat store of water and 102 bottles of PCM (12 % PCM, 60 bottles of sodium acetate with graphite in the upper part of the tank and 42 bottles of paraffin RT27 in the lower part) additional to the tests given in Report C3.

For the heating tests there was no significant difference between the pure water tank and the one filled with PCM bottles. For the DHW test it could be seen, that the burner had to switch on more often with the PCM store due to the lower water content and the low heat transfer from PCM to water.

Further work is required to optimize the heat exchange from water to PCM and to get a higher ratio of PCM in a water store.

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
Norway
Portugal
Spain
Sweden
Switzerland
United States

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”.

This report presents the improvements brought by two IEA SHC Task 32 teams to their PCM storage units.
The first experiments have been described in Report C3 of Task 32.
This report brings the latest monitoring results on two systems.

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.

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for the Swiss Federal Office of Energy

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Contents

1 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 University of Applied Sciences Western 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 Report C3.

This Report C4 deals with the updates since Report C3. For two systems (Lleida University, Spain and University of Applied Sciences Western Switzerland in Yverdon-les-Bains/Switzerland) additional measurements were performed that are described in the following.

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	University of Applied Sciences Western 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 PCM modules in DHW tanks at the University of Lleida

Luisa F. Cabeza, Cristian Solé, Marc Medrano, GREA - Research Group on Applied Energy, UdL

2.1.1 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 2-1). One of the main advantages of this type of heat stores is the good use of low temperature heat and/or waste heat.

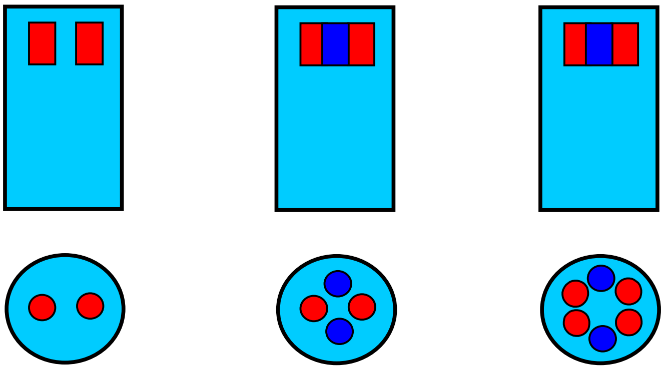

Figure 2-1 Configurations employed for experimental testing.

This idea is not new and its good performance was demonstrated in previous papers. The work presented first 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 modelling of such a system with TRNSYS was also carried out.

The idea behind the development of this system is the combination of the advantages of stratified sensible heat storage and latent, phase change heat storage; i.e. a hot water storage tank with stratification where a PCM is placed at the top part of the tank.

Many parameters, both with dimension and dimensionless, have been defined in order to characterise the level or probability of stratification, but it is difficult to decide which one to use, since there is no work comparing their suitability or performance. The project report “Dimensionless parameters used to characterize water tank stratification” of Task 32 identifies the most important and used dimensionless numbers to characterize stratification in water tanks and determines their suitability. These numbers are compared using experimental results obtained working with different flow rates. The influence of the most important variables and the reliability and precision with which these numbers describe stratification in a water tank are determined. Richardson number results to be the only

parameter that defines stratification correctly in a water tank, while Mix number presents some problems and a bad behaviour when comparing experiments using different flow rates. The other studied numbers do not describe stratification by themselves.
Richardson Number was chosen to compare a water tank and a PCM-water (Phase Change Material) tank with stratification. PCM is good for high energy density if there is a small temperature change, because then the latent heat is much larger than the sensible heat. On the other hand, the temperature change in the top layer of a hot water store with stratification is usually small as it is held as close as possible at or above the temperature for usage. In the system studied the Phase Change Material is placed at the top of the tank, therefore the advantages of the stratification still remain. The aim of this work is to demonstrate that the use of PCM in the upper part of a water tank does not destroy the stratification phenomenon and more energy is stored into the tank and it is available for the corresponding applications. For such purpose stratification and energetic analysis were done and experiments for DHW applications were carried out in a water tank and a PCM-water tank with different geometries for the PCM placement. Similar work was done by the authors for central heating applications.

2.1.2 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 and Figure 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.

Figure 2-2 Solar thermal collectors from Takama.

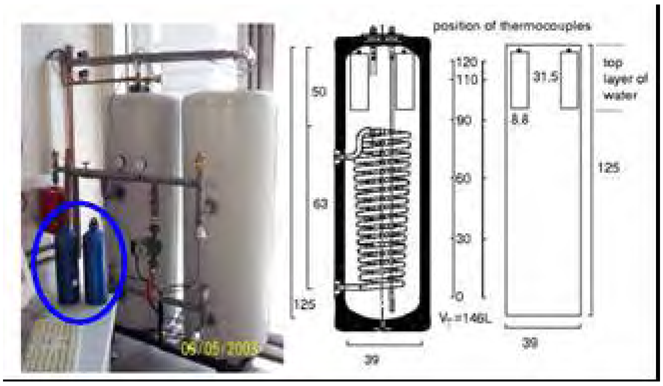

Figure 2-3 Hot water tanks from Lapesa and PCM modules.

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 Figure 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 – 5 W/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 60 0L/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.

New experiments were done to ensure that stratification of the water tank is not destroyed when the PCM modules are included in it. For the experiments, a commercial water tank with a capacity of 287 L for vertical floor installation was used (Figure 2-4). It has a coil heat exchanger at the top part of the tank, usually used to connect it to the boiler, and another one at the bottom of the tank, usually used for the solar loop.

To study thermal stratification inside the tank and the effect of the PCM, the tank was divided in six layers at different height. The registered data of the system were temperature of the water at 26, 51, 76, 101, 126 and 151 cm from the top of the tank, ambient temperature, inlet and outlet temperature of the water, temperature of the PCM inside the coil, and water mass flow rate. The temperature sensors were Pt-100 DIN-B. The flow meters used were Badger Metter Prime Advanced with a flow range from 0.85 to 17 L/min and an accuracy of 0.25% for velocities lower than 5 m/s and 1.25% for velocities higher than 5 m/s. The maximum temperature of the fluid was 150 ºC. The data were registered with a two data-loggers STEP DL01-CPU, connected to a computer.

The tank was connected to a test rig installation for performance characterization of stores (Figure 2-4). Two different pumps were used: Wilo TOP –S50/15 for the charging circuit, and Wilo-Star-ST 20/4 for the discharging circuit.

In the tank, the inlet port situated at the bottom of the tank had a stratifier to achieve a good distribution of the water and to prevent the water jet from destroying the stratification of the tank.

Figure 2-4 Test ring installation and commercial tank used in the experiments.

Experiments were done placing the PCM in different ways in the tank. First, experiments with no PCM were done, to have a reference case. Then, PCM was added in the tank with cylindrical modules, as done previously by the authors. Finally, the PCM was added filling up the upper coil of the water tank, but since the amount of PCM was not enough, three modules were also placed in the tank (Figure 2-5). The idea of using the upper coil to place the PCM in the tank was for industrialization purposes; furthermore, the placement of the PCM in the coil gives a higher heat transfer surface between the water and the PCM.

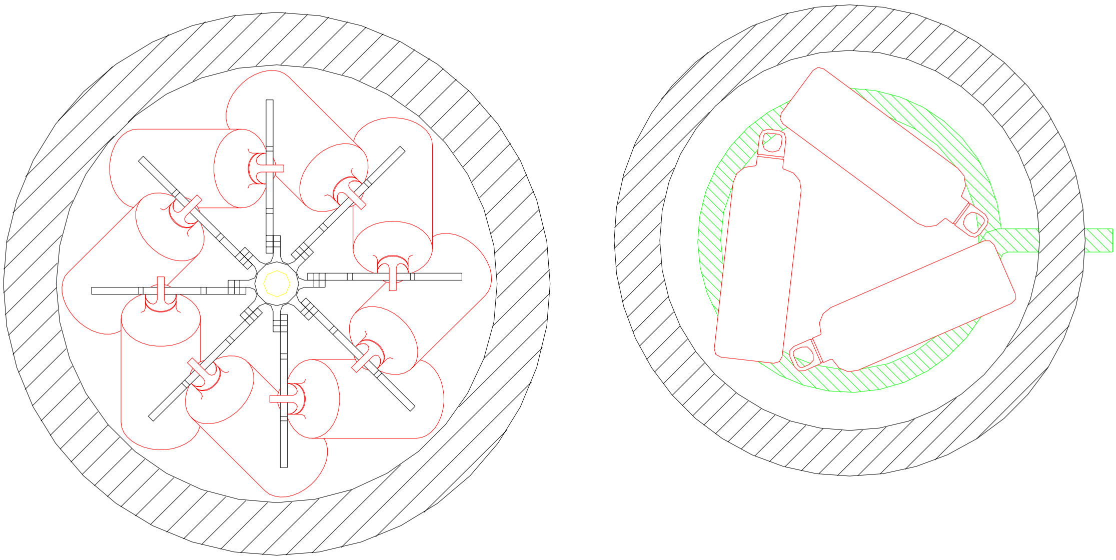

Figure 2-5 Location of the PCM in the water tank. Left: 8 cylindrical modules; right: upper coil and 3 cylindrical modules.

The amount of PCM placed in the each cylindrical bottle was 1150 g, which means that the 8 modules configuration had 9200 g (4.18% of the water volume). In the coil/modules configuration, the coil had 4900 g of PCM and the 3 modules 1050 g each one, meaning 8050 g in total (4.92% of the water volume – see that the PCM included in the coil does not take volume to the water). The amount of PCM placed into the coil results in an experimental density of 0.5 kg/L, significantly lower than the value provided by the manufacturer (1.3 kg/L).

The experimental work consisted of charging and discharging tests. The discharging experiments were performed introducing cold water (24ºC) at the bottom part of the tank, and extracting hot water (65ºC) from the top. The flow rate was regulated using a valve. The system worked in a closed loop, cooling the water going out of the top part of the tank. The cooling was done using tap water at public drinking water system supply temperature passing through a plate heat exchanger. In these experiments the inlet with stratifier was used.

In the charging tests, hot water (65ºC) was introduced at the top part of the tank, and cold water (24ºC) was extracted from the bottom. The flow rate was regulated using a valve. The heating system was an electrical resistance of 5 kW of nominal power, ensuring an inlet temperature of 65ºC. The temperature control was done with a PID control system used in the test ring installation. The system worked in a closed loop, heating the water going out of the bottom port of the tank.

2.1.3 Laboratory Test Results

Figures 2-6 – 2-9 show the results from the laboratory tests performed in Lleida.

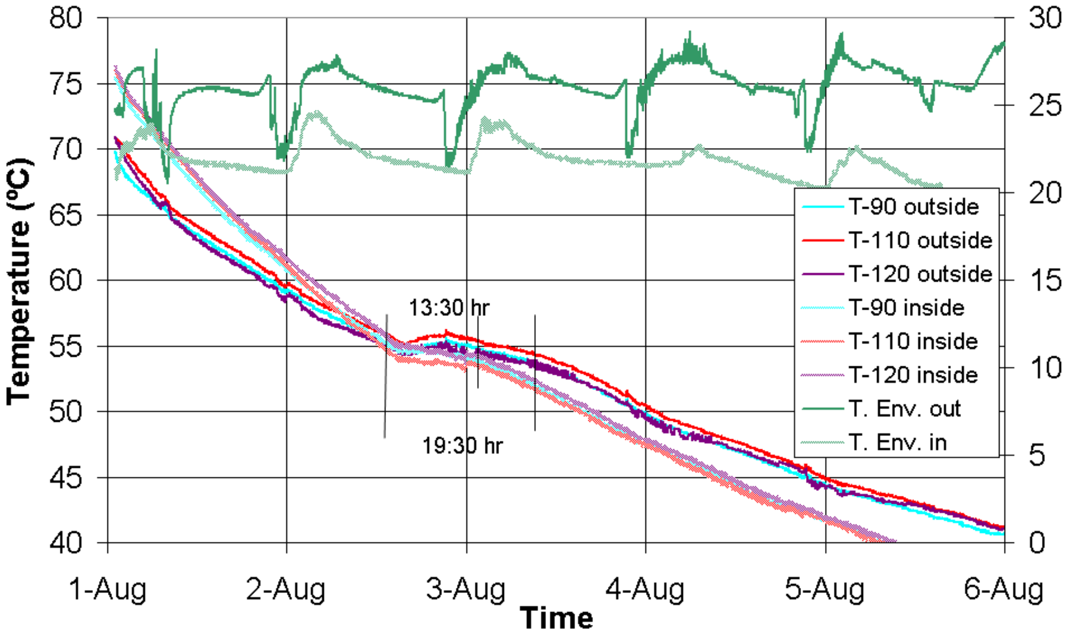

Figure 2-6 Cooling down experiments with sodium acetate trihydrate with graphite.

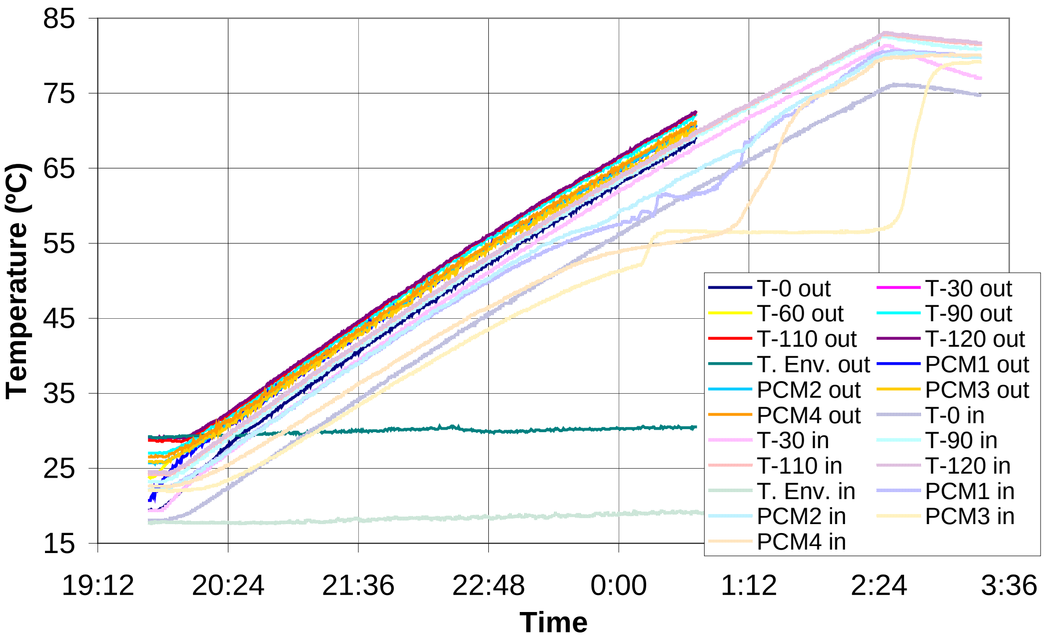

Figure 2-7 Charge experiments with sodium acetate trihydrate with graphite.

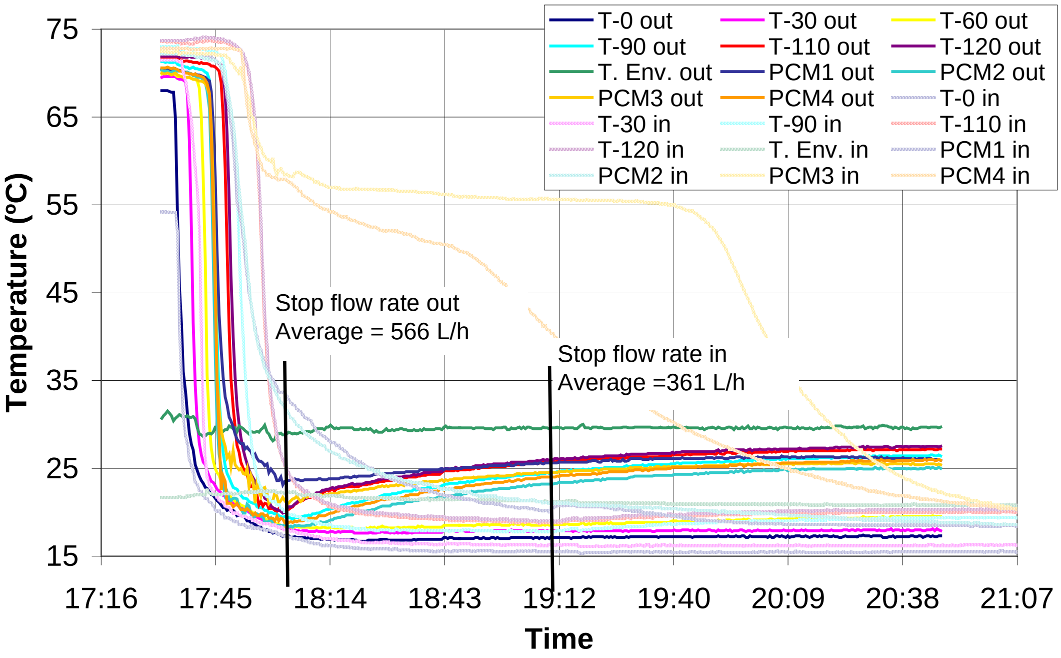

Figure 2-8 Discharge experiments with sodium acetate trihydrate and graphite.

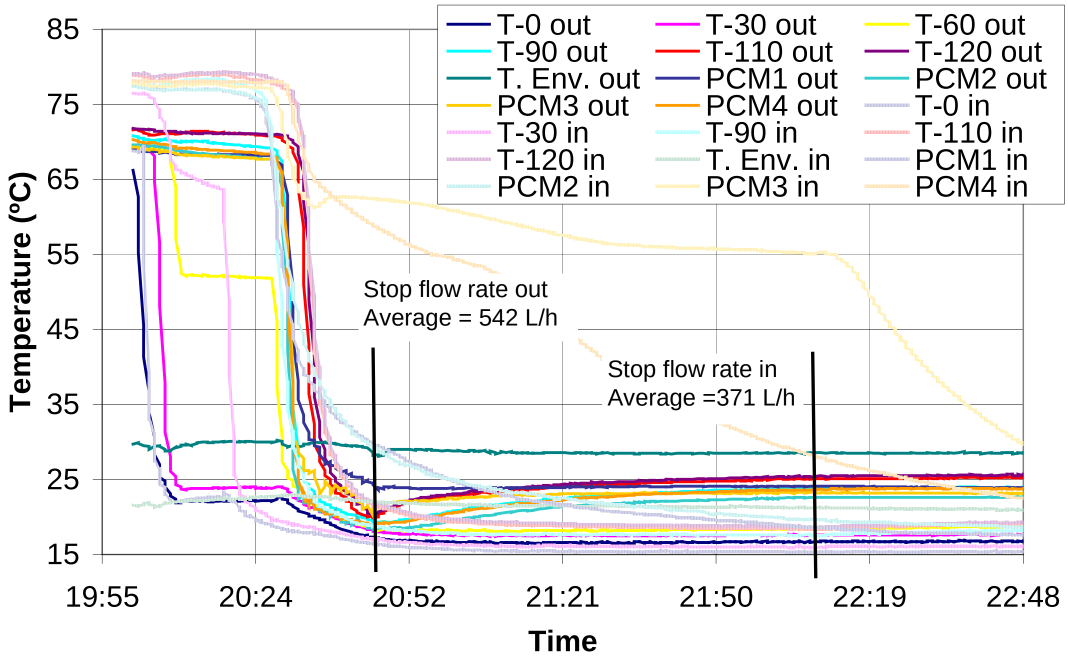

Figure 2-9 Results from cycling experiments with sodium acetate trihydrate and graphite.

Table 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

In the experiments of the stratification of the water tanks, and for comparison purposes, experiments were performed with three systems. First with only water, second with PCM in 8 modules, and third with PCM in the upper coil of the tank (in this last case, also 3 modules were added to have about the same amount of PCM as in the case with only modules).

For each case, charging and discharging experiments were done simulating a domestic hot water system. For each procedure different flows were compared (2, 3, 4 and 5 L/min).

Figure 2-10 presents the temperature profile of the discharging process at 3 L/min of the tank filled up only with water. Figure 2-11 shows the same results for the water tank with PCM in 8 modules and, Figure 2-12 the results for the tank with PCM in the coil. In the three figures, the results of two experiments are presented, showing good reproducibility in them.

In Figure 2-11 and Figure 2-12, the effect of the PCM is seen in the temperature of the top layer ($T1_{260}$, $T2_{260}$). As expected, Figure 2-12 also shows this effect in a lower sensor, since the PCM in the coil is at a lower position than in the other tank.

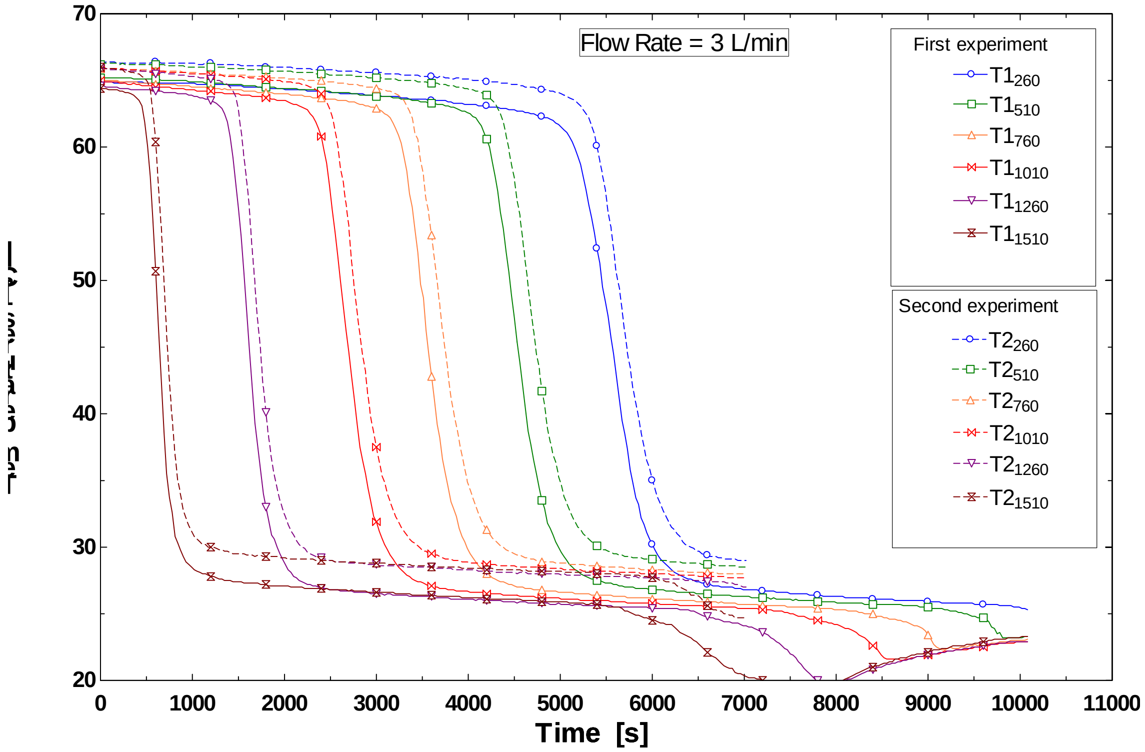

Figure 2-10 Temperature profile, discharging of reference tank at 3 L/min

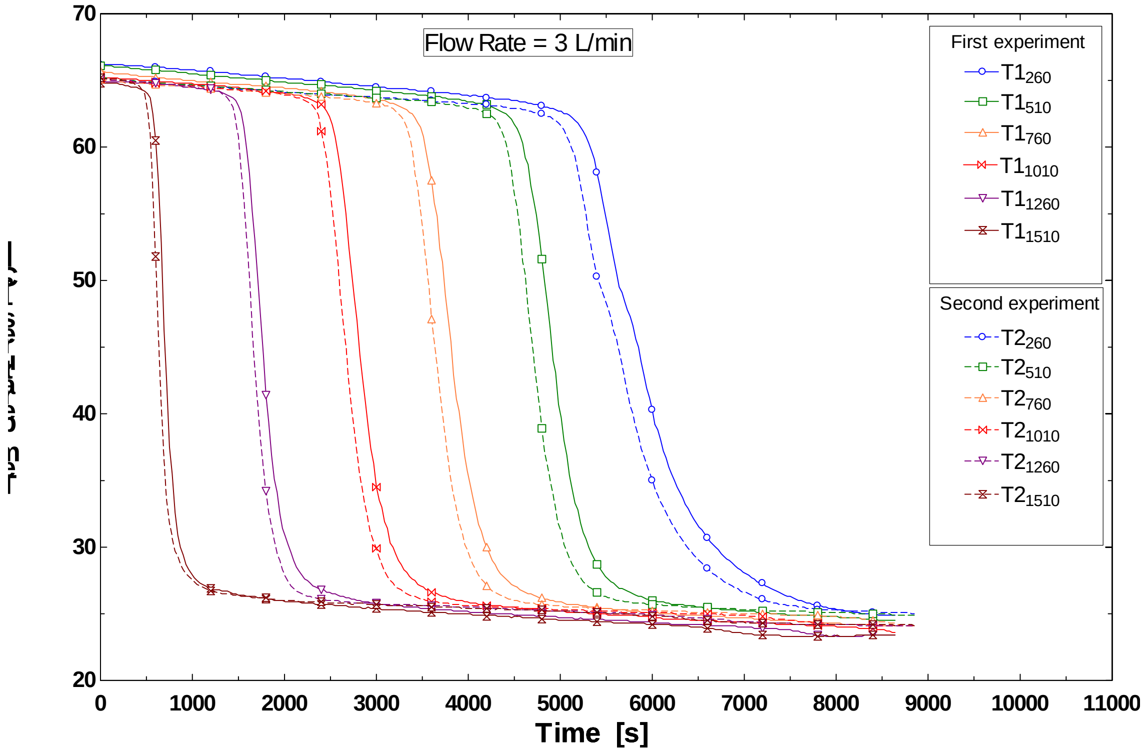

Figure 2-11 Temperature profile, discharging of tank with 8 PCM modules at 3L/min

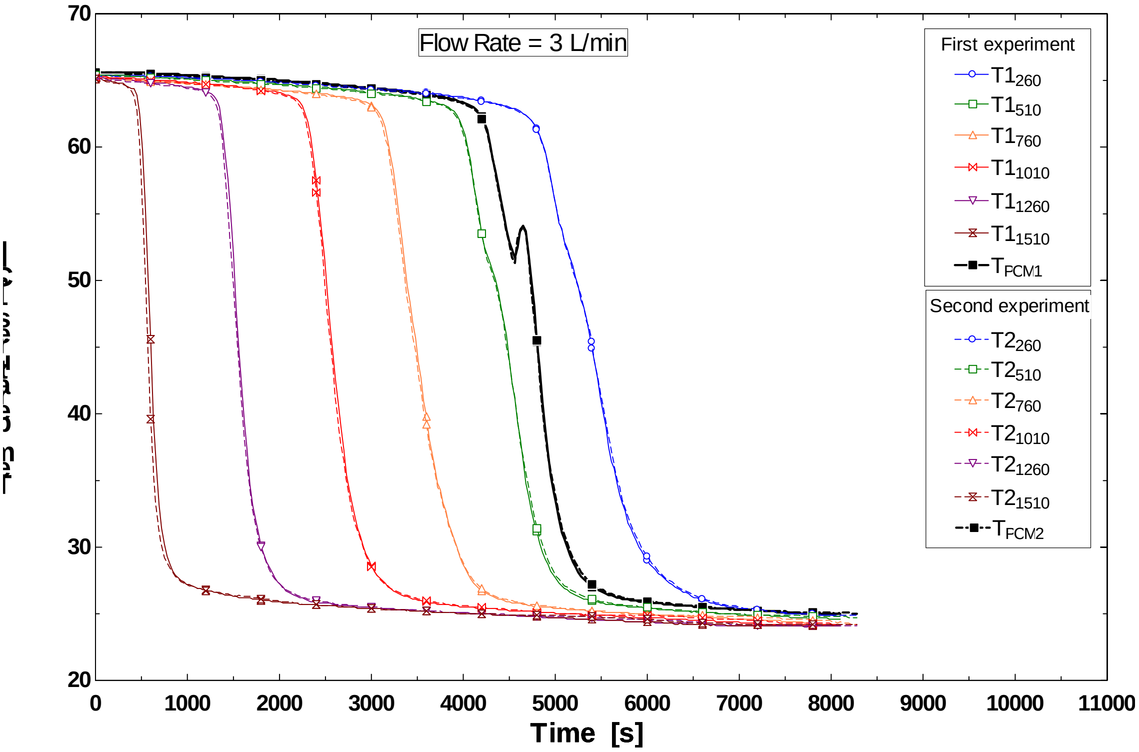

Figure 2-12 Temperature profile, discharging of tank with 3 PCM modules and PCM coil at 3 L/min

Table 2-2 to Table 2-4 show the results of the energy balance of these experiments at 2, 3, 4, and 5 L/min. Acceptable deviation from the two energy balances of 5-10%, within the experimental error, is observed. No significant differences comparing the PCM-tanks with the reference water tank are observed. This is the expected result, as the theoretical increase of energy storage capacity is only of 2% in this application of domestic hot water. Better results should be expected for central heating, where the temperature gradient between outlet and inlet temperature is lower and the latent heat effect of PCM is higher.

Table 2-2 Energy balance for discharging experiments without PCM

Flow rate	/ΔE_{tank} / [kJ]	/$E_{in} - E_{out}$ / [kJ]	/Difference/ [kJ]	Energy Balance [%]
2 L/min	48330	51447	3117	93.55
3 L/min	47667	49070	1403	97.05
4 L/min	45559	47684	2125	95.34

Table 2-3 Energy balance for discharging experiments with PCM inside 8 modules

Flow rate	/ΔE_{tank} / [kJ]	/$E_{in} - E_{out}$ / [kJ]	/Difference/ [kJ]	Energy Balance [%]
2 L/min	46641	50301	3660	92.15
3 L/min	47129	51294	4165	91.16
4 L/min	46423	50114	3691	92.05
5 L/min	46565	50412	3847	91.74

The stratification of the tanks during the charging and discharging processes was evaluated. Figure 2-13 to Figure 2-15 present the results of the stratification evaluation.

Table 2-4 Energy balance for discharging experiments with PCM inside the coil and 3 modules

Flow rate	$/\Delta E_{tank}/$ [kJ]	$/E_{in} - E_{out}/$ [kJ]	/Difference/ [kJ]	Energy Balance [%]
2 L/min	48583	48318	265	99.45
3 L/min	48224	47814	410	99.14
4 L/min	48547	48072	475	99.02
5 L/min	48458	47069	1389	97.14

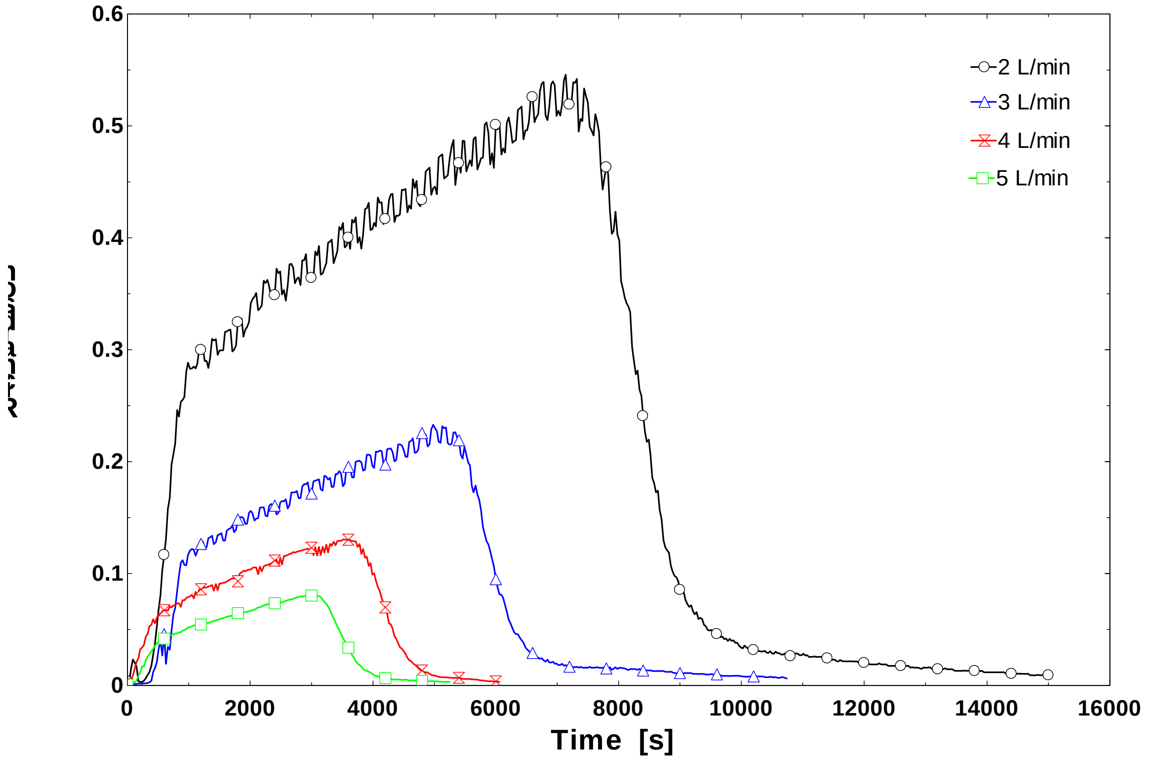

Figure 2-13 Richardson number, charging, water tank

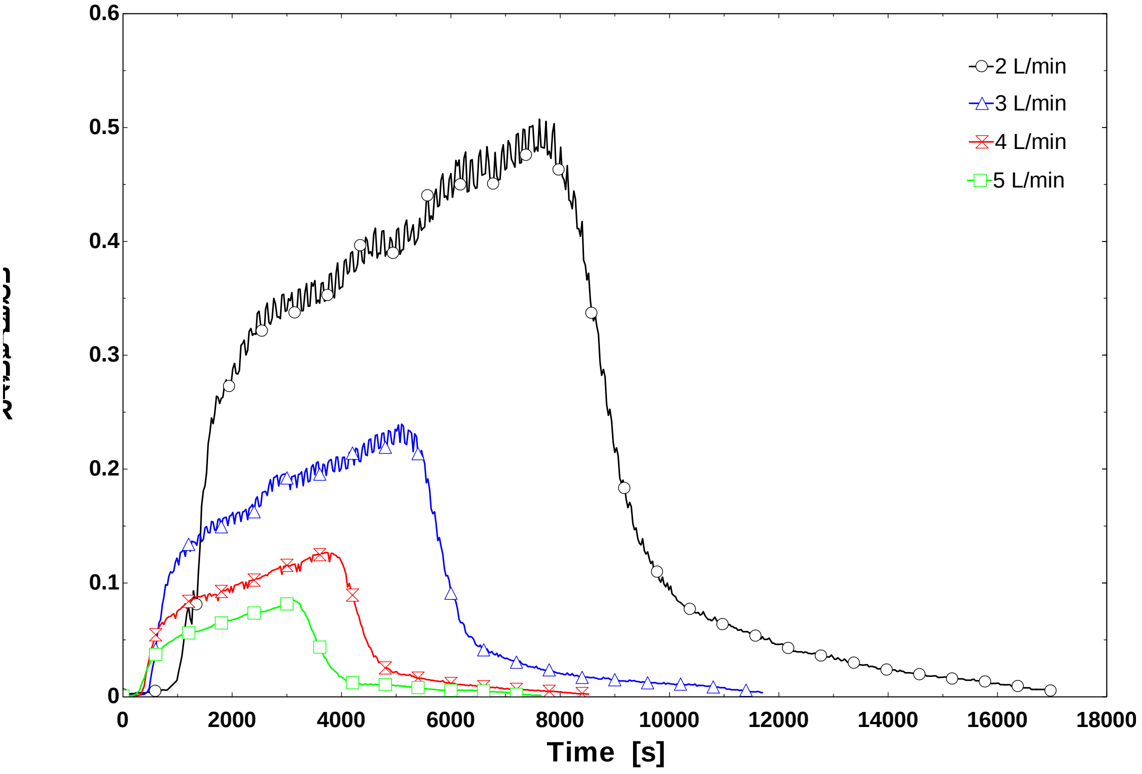

Figure 2-14 Richardson number, charging, water tank with 8 modules

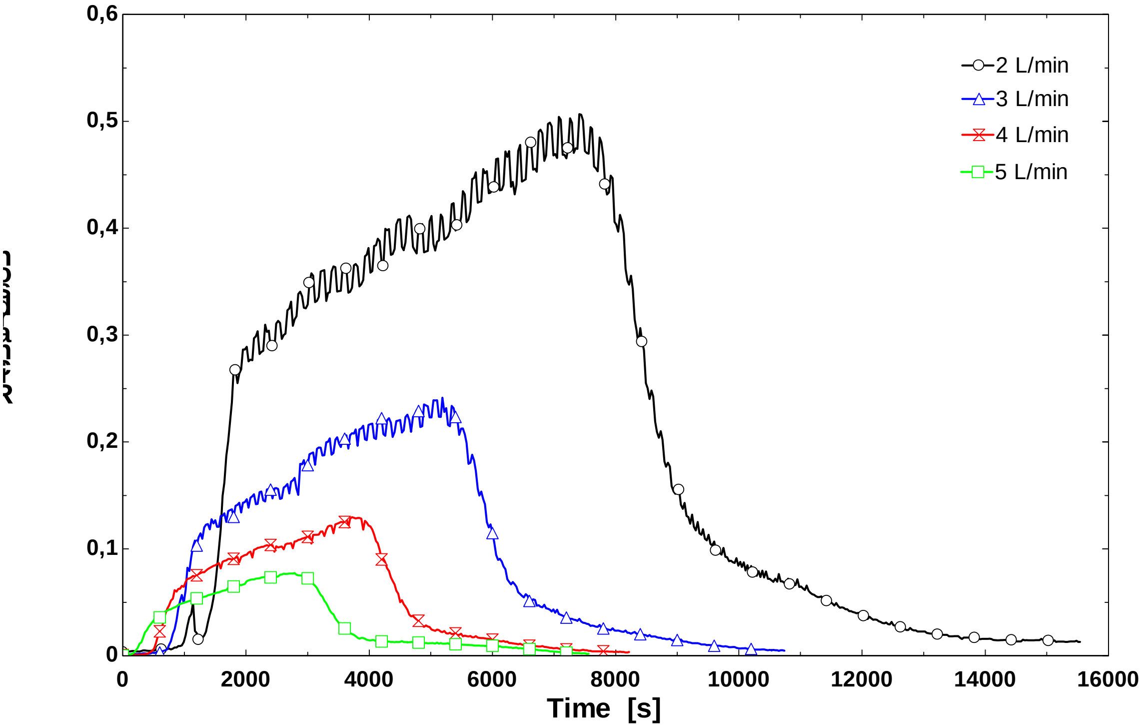

Figure 2-15 Richardson number, charging, water tank with 3 modules and coil

No significant differences can be observed when comparing Richardson number for each tank. Maximum and minimum values and Richardson tendency for each tank were very similar, which means all tanks present a good stratification. Therefore, one can conclude that the inclusion of PCM at the top of a domestic hot water tank does not destroy or perturb its stratification.

A small modification on the Richardson tendency was observed in both PCM-tanks. The difference is too small to be considered relevant, but it coincides in time with the PCM melting process. The final stratification in both PMC-tanks results in the same as for the water tank.

On the other hand, a PCM-tank with more PCM in the upper part would not be very useful for domestic hot water applications, since there will be no water at the top layers to take advantage of the effect of the PCM.

Experimental results gave acceptable deviation from the energy balance of 5-10%, within the experimental error. No significant differences comparing the PCM-tanks with the reference water tank were observed. Better results should be expected for central heating, where the temperature gradient between outlet and inlet temperature is lower and the latent heat effect of PCM is higher.

Studying the stratification of the tanks, no significant differences can be observed. Richardson number presents similar results for all tanks. A small modification was observed in both PCM-tanks, although the final stratification was the same for all tanks. If using much more PCM in the upper part of the tank the perturbation could be higher.

On the other hand, a modification of the stratification in the tank could only occur for partial charging/discharging processes, since during the phase change process the water temperature at the top layers of the tank will remain constant and as a result also will the stratification. This effect will result in a longer time for the tank to get the same stratification as a water tank (since it will also take longer to the top layers to get warmer when the PCM is melting). On the other hand, during the discharging process, the tank will keep stratification longer (since it will also take longer for the top layers to get cooler when the PCM is solidifying).

Considering the domestic hot water application, it makes no sense to use more PCM, since there will be no water at the top layers to take advantage of its effect. Therefore, one can conclude that for domestic hot water applications, the stratification of a tank is not destroyed or perturbed by the addition of PCM at the upper part. Only the addition of much more PCM could affect significantly the stratification.

The small effect seen in the DHW application is expected as the use of PCM is only an advantage against water when a small temperature shift takes place during the process considered.

2.1.4 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 Figure 2-16 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.

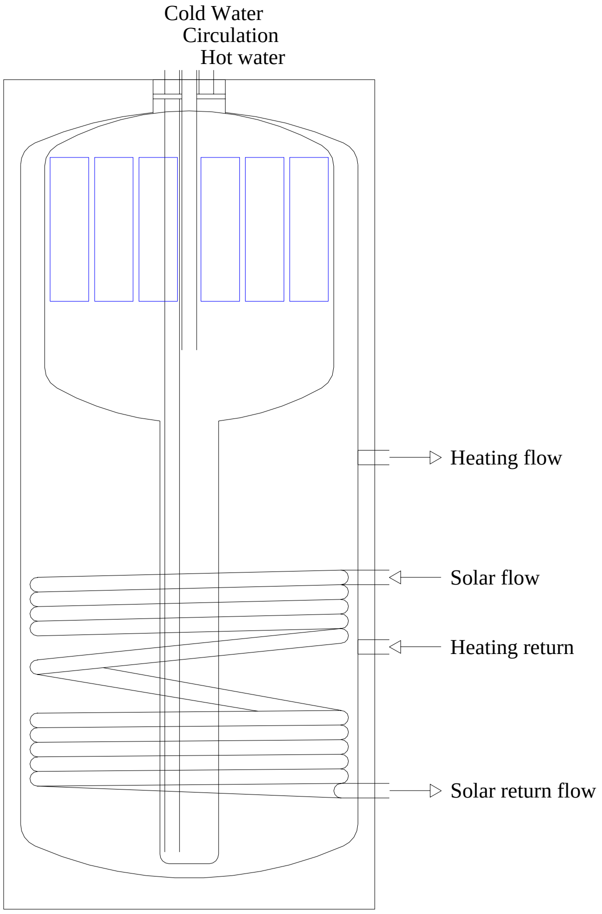

Figure 2-16 Combistore prototype design.

2.1.5 Acknowledgements

The authors would like to acknowledge the companies Lapesa S.A., Takama and SGL Technologies for their collaboration in this research. The work was partially funded with the project CICYT DPI2002-04082-C02-02, the project ENE2005-08256-C02-01/ALT and the project 2005SGR 00324. Dr. Marc Medrano would like to thank the Spanish Ministry of Education and Science for his Ramon y Cajal research appointment.

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2.2 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

2.2.1 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.

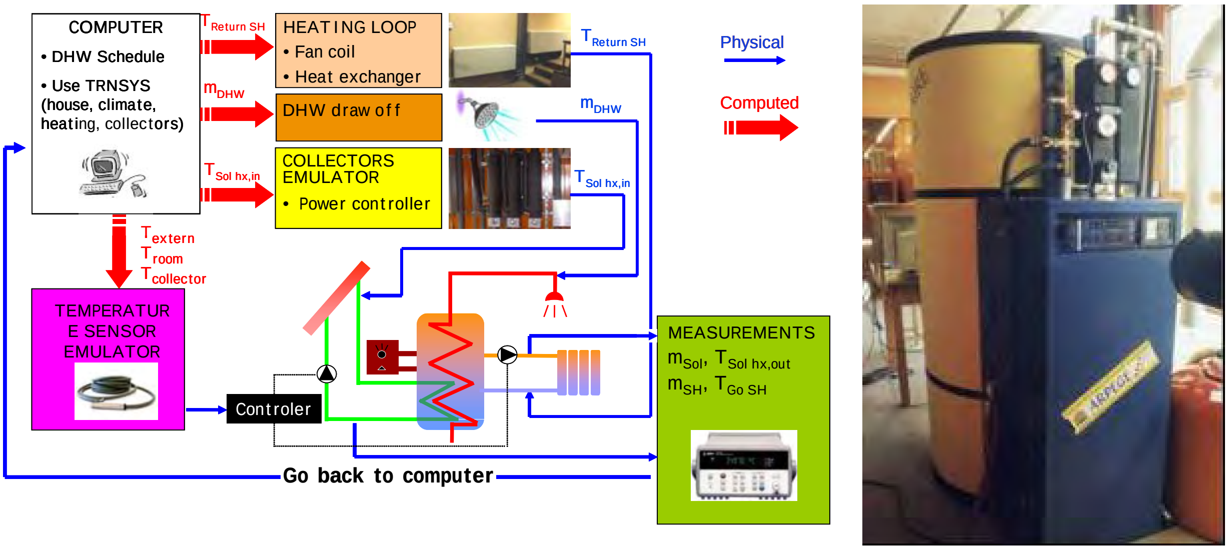

Figure 2-17 Principle diagram of test bench and combisystem Arpege.

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.

2.2.2 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 2-18.

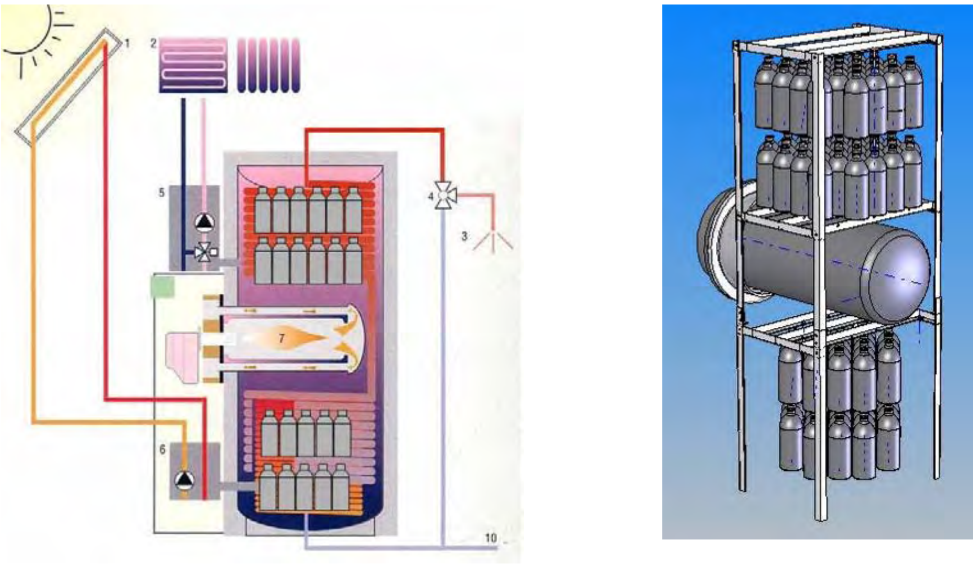

Figure 2-18 Arpege drawing with PCM bottles.

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.

2.2.3 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 2-19.

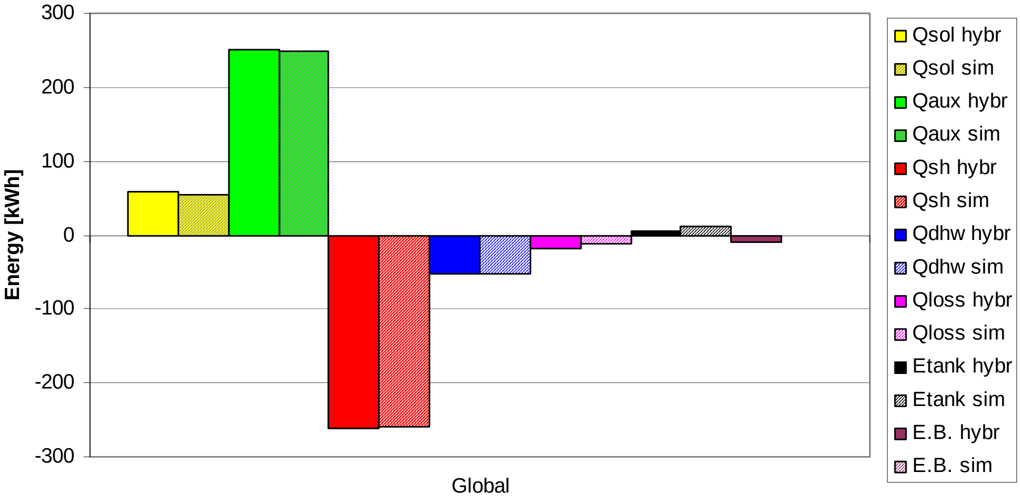

Figure 2-19 Comparison of measurements and TRNSYS simulations. Yellow=solar; Green=auxiliary; Red=heating demand; Blue=DHW; Pink=thermal losses from tank; Black=internal energy tank; Brown=energy balance

Table 2-5 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 2-20.

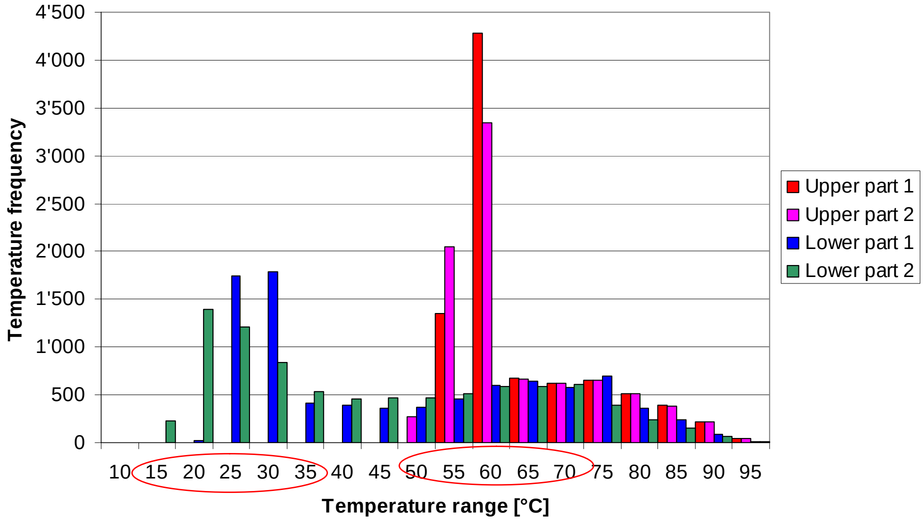

Figure 2-20 Temperature frequency according to the height level storage.

2.2.4 Development Status

1) Combisystem performance

A set of 102 bottles filled with paraffin (40%) and sodium acetate trihydrate (60%) are plunged in the water tank. The occupied volume represents approximately 15% percent of the tank volume, as show in Figure 2-18.

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 were undertaken. The results are compared to the simulation results, in order to validate the model developed for TRNSYS (See Report C5).

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 2-21. This second set of experimental data, were helpful to compare the results obtained with our simulation model.

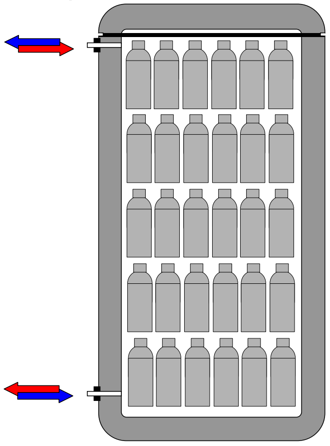

Figure 2-21 Water tank fill with PCM bottle

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 2-22.

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 2-23.

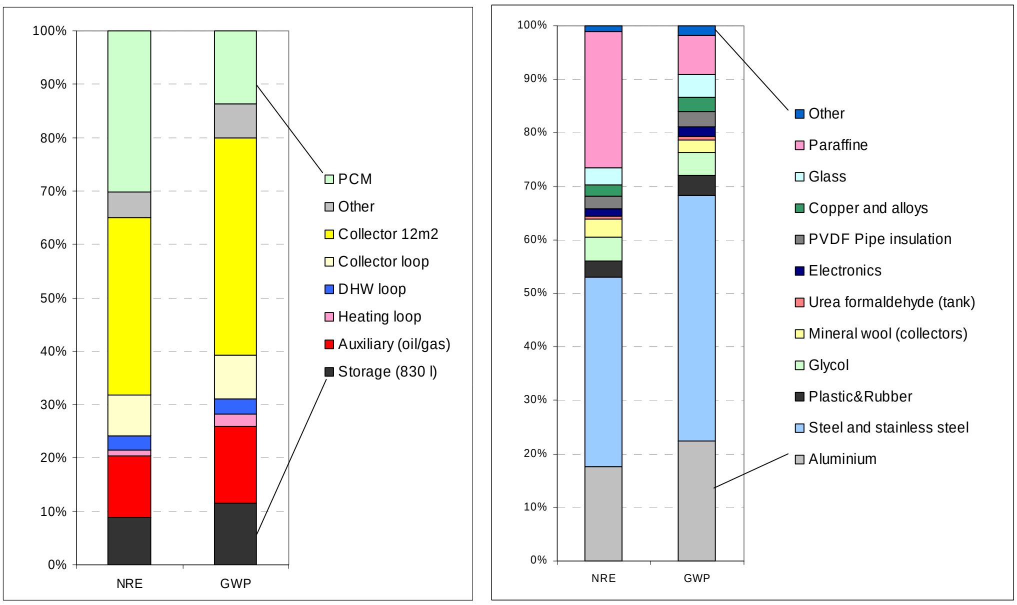

Figure 2-22 LCIA of the Arpege system by elements (left) and by materials (right)

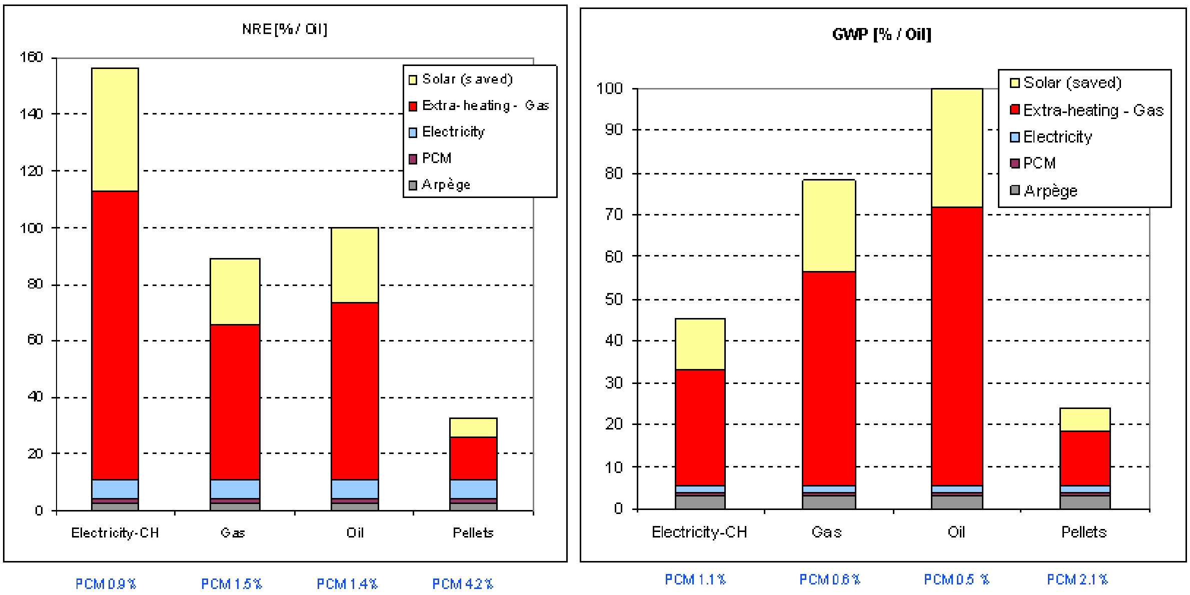

Figure 2-23 LCIA of the Arpege system for different energy heating vectors.

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.

4) Sodium acetate trihydrate

For the experiment, 2 PCM types were selected:

1. Sodium acetate with graphite (SGL Carbon) plunged in the upper part of the water tank.
2. Paraffin RT27 (Rubitherm) in the lower part of the tank. The temperatures of phase change are respectively 58 and 27 [°C].

The PCMs’ properties are given in Table 2-6.

Table 2-6 Design PCM characteristics

Characteristic	**Paraffin RT27**	**Sodium acetate + graphite**
Thermal conductivity [W/m.K]	0.2 (solid and liquid)	4 (solid and liquid)
Density [kg/l]	0.9 (solid) – 0.75 (liquid)	1.3 à 1.4 (solid and liquid)
Cp [kJ/kg]	1.8 (solid) – 2.4 (liquid)	2 (solid and liquid)
Latent heat [kJ/kg] [kJ/l]	180 150	150 240
Phase change temperature [°C]	27	58

Figure 2-24 Temperature Sodium acetate with graphite (left) and paraffin RT27 (right)

A total number of 102 bottles have been installed in the water tank, 60 of sodium acetate with graphite in the upper part of the tank and 42 of paraffin RT27 in the lower part (Figure 2-18). The PCM volume percentage is 21% in the top part and 14% in the bottom part. The global percentage is about 12%. This low value is due to the volume of the solar and DHW heat exchangers, and the combustion chamber located in the storage tank (Figure 2-18).

A) Heating

The test duration is 7 days with two different winter periods of the Zürich climate, for a single family house with a 140 m^2 floor area and a heat demand of 30 [kWh/(m^2.a)]. The DHW demand is 7.5 [kWh/day]. The first weather sequence is a medium sunny winter and the second one is a high sunny winter

Figure 2-25 and Figure 2-26 show the comparisons of the energy contents with and without PCM for the 2 selected climates. The variant with PCM shows a reduction between 2 and 3% on the gas consumption. Due to the accuracy of the test bench, there is more or less energy use in the space heating loop. Thus these differences of 2 or 3% are inside the experimental errors.

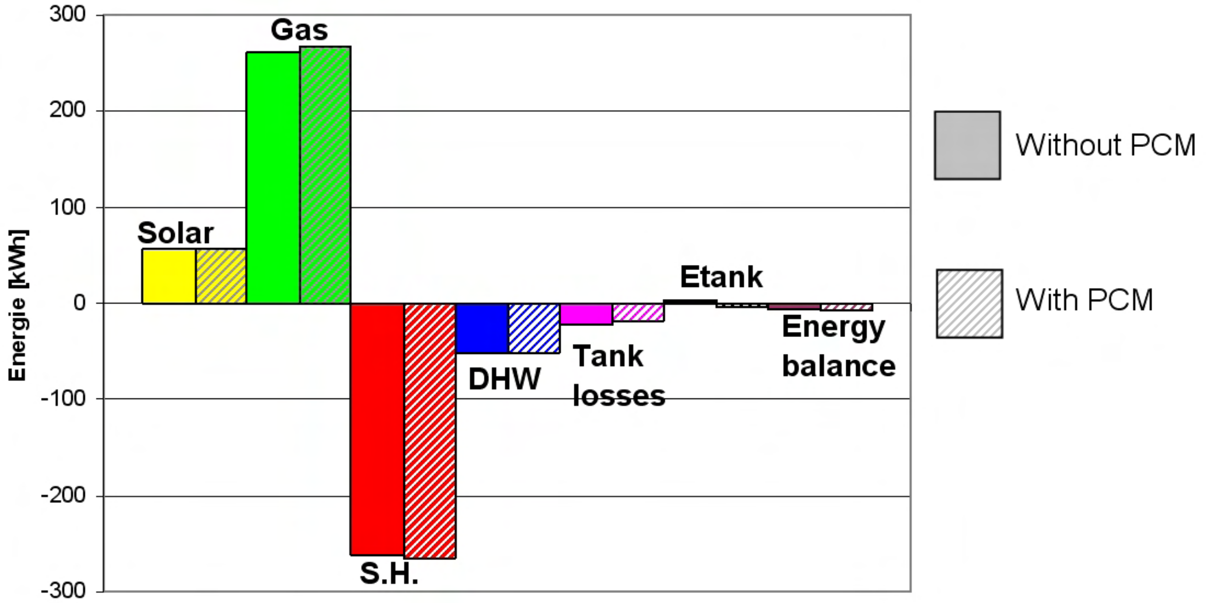

Figure 2-25 Comparison measurement with and without PCM during 7 days (medium sunny winter period).

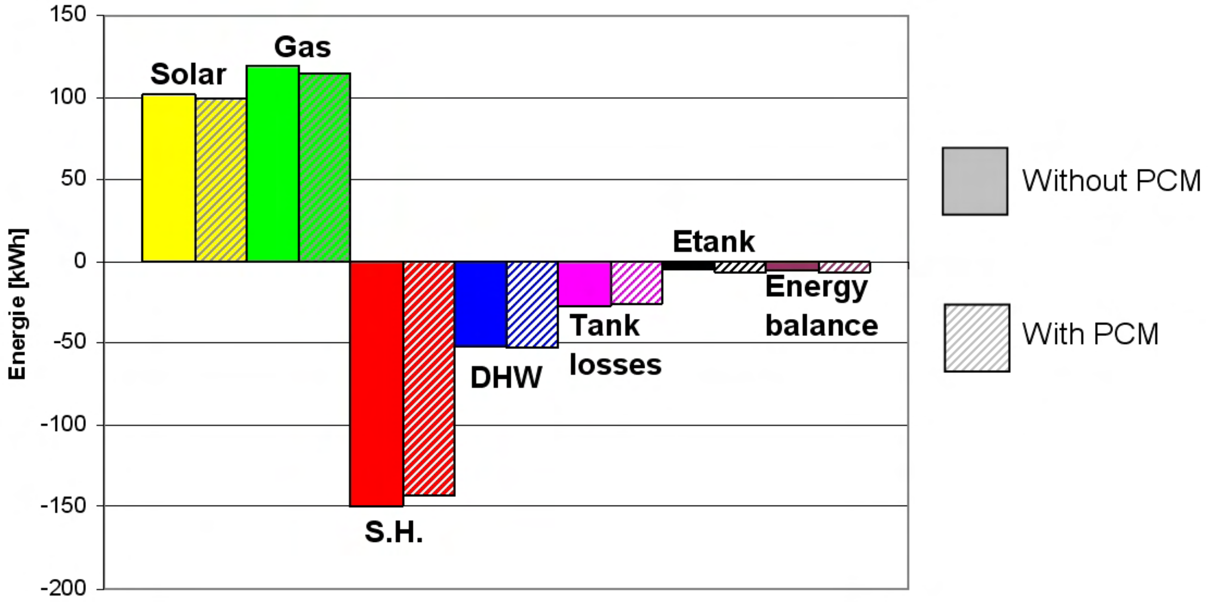

Figure 2-26 Comparison measurement with and without PCM during 7 days (high sunny winter period).

B) DHW

Some DHW tests have been undertake with a large and small draw off. Figure 2-27 shows the temperature level at the upper part of the tank. The increase of the temperature occurs when the burner is on. The decrease of the temperature is due to the DHW draw off. With PCM (red curve), there is some change due to the low heat transfer between water and PCM module. Thus, with PCM, there is 20 to 25 % more burner starting and 20 to 25 % less of burner operating time.

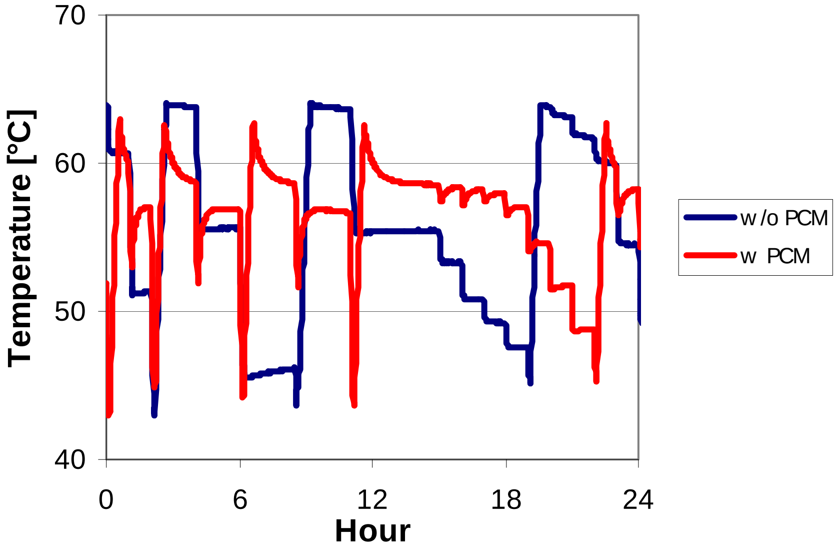

Figure 2-27 Comparison of the behaviour during DHW draw off with and without PCM

These measurements show that it is difficult to improve the performances of this solar installation using PCM modules. At this time, it is difficult to conclude that phase change material does offer an advantage. The total volume of the PCM modules that can be placed in the water tank is not very high (about 12%). Effectively, different internal heat exchangers are present inside the water tank. Furthermore, the heat transfer between water and PCM is not good with the diameter of the bottles used.

2.2.5 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.

SGL Carbon company for provide sodium acetate with graphite which allows us to achieve measurement.

2.2.6 References

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3 COMPARISON OF PROTOTYPES

There were 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 and increase of power input/output is tested. Applications are free-cooling and DHW tanks
- In University of Applied Sciences Western 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.

- 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 of Report C3.

4 Final conclusions

In this C4 Report additional analysis compared to Report C3 published in May 2007 of the systems of Lleida University, Spain University of Applied Sciences Western Switzerland in Yverdon-les-Bains/Switzerland (HEIG-VD) are presented

In Lleida University, Spain the same store with three different fillings was used:

- pure water,
- aluminium bottles filled with sodium acetate trihydrate with graphite and
- the coil of the heat exchanger in the middle of the tank with additional three bottles filled with sodium acetate trihydrate with graphite.

Discharge flow rates were performed. There was no significant increase of the energy content of the three tanks, but as the maximum theoretical increase was only 2 % this was expected. The main focus of theses experiments was laid on the level of stratification within the tanks. It could be shown, that the stratification was not disturbed by the (little amount) of PCM in the store.

At HEIG-VD, Switzerland, a 7 day measurement for a heating period assuming a sunny winter period and a DHW test over 24 hour with a large and a small draw off were performed for a store with pure water and in comparison with a heat store of water and 102 bottles of PCM (12 % PCM, 60 bottles of sodium acetate with graphite in the upper part of the tank and 42 bottles of paraffin RT27 in the lower part) additional to the tests given in Report C3. For the heating tests there was no significant difference between the pure water tank and the one filled with PCM bottles. For the DHW test it could be seen, that the burner had to switch on more often with the PCM store due to the lower water content and the low heat transfer from PCM to water.

Further work is required to optimize the heat exchange from water to PCM and to get a higher ratio of PCM in a water store.