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Laboratory testing of solar combi system with compact long term PCM heat storage

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Abstract

To enable the transition from fossil fuels as a primary heat source for domestic hot water preparation and space heating solar thermal energy has great potential. The heat from the sun has the disadvantage that it is not always available when there is a demand. To solve this mismatch a thermal seasonal storage can be used to store excess heat from the summer to the winter when the demand is higher than the supply. Installing a long term thermal storage in a one family house it needs to be compact and sensible heat storages are not suitable. A latent heat storage with a phase change material (PCM) can provide a more compact way of storing heat. Sodium acetate trihydrate (SAT) is a good candidate material as it has a relatively high heat of fusion and in addition it has the ability to supercool to room temperature without solidifying. In this paper results from the test of a solar combi system with a latent heat storage with SAT is presented. The SAT heat storage modules were heated to 80 °C by the solar collectors 53 times in the test period from June to November 2015 and this enabled the modules to supercool. Supercooling was achieved for 39 days for a SAT module after which 11 kWh of heat were discharged.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: Solar combi system; System demonstration; Thermal storage; Sodium acetate trihydrate; SAT; Phace change material; PCM; Solar collector; stable supercooling;

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1. Introduction

As the world faces more and more severe challenges with changing climate due to the rapid rise in CO_2 in the atmosphere, the search for low carbon energy sources is accelerating. In Europe almost 50 % of all energy use is in the form of heat, and if focusing on domestic use 86% of the energy used by European households is heat. Therefore it is imperative that new low carbon heat sources are utilized [1].

Heat from the sun is a source of low or no carbon heat. The use of the sun as a heat source for domestic hot water and for space heating has been done for centuries [2]. One major disadvantage of solar energy is that it is an intermittent heat source and in temperate climate zones the energy available from the sun in the winter does not cover the demand. To cover day and night fluctuations a simple hot water tank is suitable since a sensible heat storage can cheaply and easily be installed. However when it comes to storing heat from the summer where the supply of energy from the sun surpasses the demand to the winter where the heat supply from the sun is not sufficient, a sensible heat storage would have to be very large to cope with the inevitable thermal losses.

There are however other storage methods than sensible heat; chemical heat storage and latent heat storage. Both storage technologies have the potential to store heat in a more compact form and they do not have a continuous heat loss problem as the sensible heat storages.

This paper focus on a solar combi system with a heat of fusion storage based on the phase change material (PCM) sodium acetate trihydrate (SAT). SAT is a salt hydrate with several qualities which make it suitable for heat storage in one family houses:

- SAT has a relative high heat of fusion of 265 kJ/kg.
- It has the ability to supercool to ambient temperatures.
- Sodium acetate is available in large quantities.
- The price of SAT is very low compared with other heat storage materials.
- SAT is nontoxic.

When SAT has been heated to a sufficiently high temperature, above 80 °C, it is possible for the SAT to supercool below its melting point of 58 °C to ambient temperature. In this state it still contains latent heat and can stay in this state for several months [3]. When there is a heat demand a seed crystal is introduced to the supercooled SAT and in a matter of minutes the whole volume solidifies releasing its latent heat. To only release an amount of heat suitable to the demand it is necessary to divide the SAT volume into individual volumes.

2. Solar combi demonstration system description

The results presented in this paper are from a solar combi demonstration system with a latent heat storage based on SAT. The system has three main components; 22.4 m^2 solar collectors, a 735 liter tank in tank buffer storage and the PCM thermal storage actively utilizing supercooling.

2.1. Heat storage design

The PCM heat storage consisted of four individual modules containing approximately 200 kg of SAT and additives. The reason for storing the SAT in separate volumes was because the principle of supercooling was used for long term heat storage. Since the system was designed to demonstrate the concept of SAT as a compact long term heat storage the size of the storage was relatively small. This means that the system was designed with a yearly solar fraction of 80% as a goal, for a passive house under Danish weather conditions.

Each volume had its own heat exchangers, one at the top and another at the bottom. The modules performance has been studied in detail in laboratory conditions by Dannemand et al. [3] and in real operating conditions by Engelmair et al. [4].

The modules were constructed by Nilan A/S and a picture of a SAT module can be seen in figure 1.

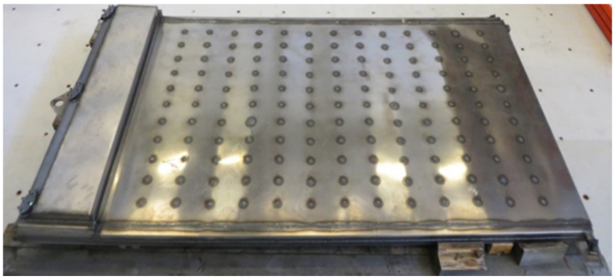

Fig. 1. A SAT module with heat exchangers at top and bottom. The dimensions are 1200 x 2400 x 60 mm [3].

2.2. Solar collector array

The solar collector array consisted of seven Kingspan HP450 evacuated tubular solar collectors with a combined collector aperture area of 22.4 m^2. This relatively large solar collector array was chosen in order to have the individual modules heated to a material temperature of at least 80 °C, even in the winter, which enables stable supercooling. Evacuated tubular collectors are suited to this task because they have superior performance when operating with high fluid temperatures compared with flat plate collectors.

In figure 2 the solar collector array can be seen mounted on a south facing roof with a tilt of 45°. The system and collectors were placed at the Technical University of Denmark in Lyngby, latitude of 56 °N, and exposed to Danish weather conditions.

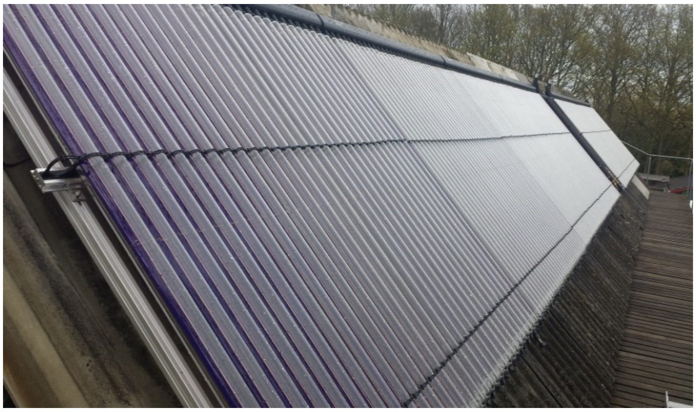

Fig. 2. The solar collector array consisting of seven Kingspan HP450 evacuated tubular solar collectors mounted on a south facing roof.

2.3. Tank in tank buffer storage

A tank in tank buffer storage was used to supply the domestic hot water and the hot water for the space heating loop. The total tank volume was 735 liters and it had an inner tank of 185 liters supplying the domestic hot water. The outer tank was heated by the solar collector loop and the space heating loop was connected to this tank volume.

The system was constructed in this way to ensure that the domestic hot water had a sufficiently high temperature. The current SAT module design did not allow for the domestic hot water to be directly supplied from the PCM storage. This was due to the low pressure tolerance of the heat exchangers in the modules and the relatively low discharge power which could be obtained in the current modules.

2.4. System design

In the system design scheme shown in figure 3 it can be seen that there are four separate loops in the system. The solar collector loop supplying heat from the solar collectors to the heat exchanger utilizing a propylene glycol/water mixture as solar collector fluid. A PCM storage and buffer tank loop using water as the heat transfer fluid at a low pressure of approximately 0.6 bars to accommodate the heat exchangers in the PCM modules. And two independent heat discharge loops one for domestic hot water (DHW) and another for space heating (SH).

All operations in the system was controlled by a custom build control system based on a National Instruments industrial computer, a CompaqRIO 9082, running control software written in LabVIEW.

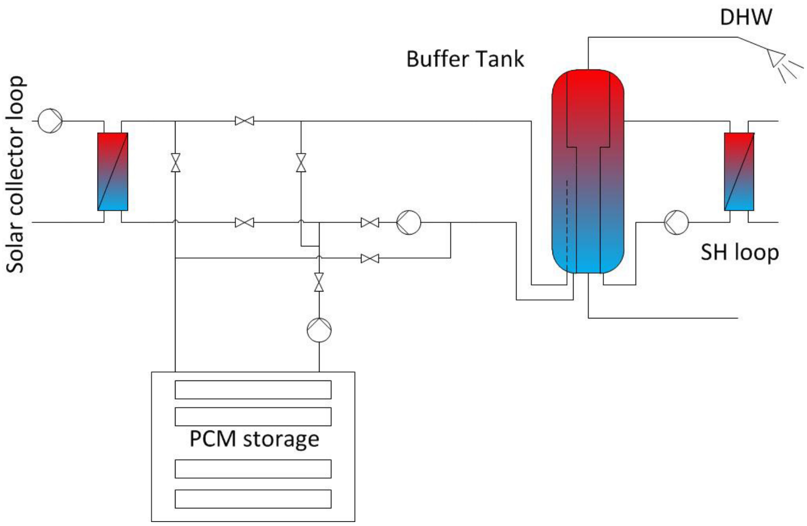

Fig. 3. A simple scheme of the solar combi system design with solar collector loop, PCM storage and tank in tank buffer storage.

2.5. System operation

The control system had a set of parameters which enabled optimal behavior of the solar combi system. As a primary objective it ensured that the buffer tank had a sufficient temperature to cover the domestic hot water and space heating demand. To keep the tank temperature high the solar heat is first transferred to the buffer tank. If this heat is not available it charges the sensible heat from the PCM heat storage modules to the buffer tank. In the event that there was no sensible heat available in the PCM modules the system would introduce a seed crystal into a module to solidify the module and subsequently discharge the latent heat to the buffer tank. After all four modules were solidified it could then switch on an electrical heating element in the tank as an auxiliary heat source.

If there was sufficient energy in the buffer tank to cover the domestic hot water and space heating demand and the system detected sufficiently high temperatures in the solar collector loop it would charge the PCM modules. In case the power from the solar collector loop surpassed the power which, at a reasonable temperature level, could be transferred to one module the system would then charge another module in parallel with the first. This could be done until all four modules were charged in parallel. As the power from the solar collectors decreased due a too low solar irradiance, fewer modules would be charged in parallel until only one was charged.

When there was insufficient heat from the solar collectors to charge the PCM storage or the buffer tank the control system went into standby mode.

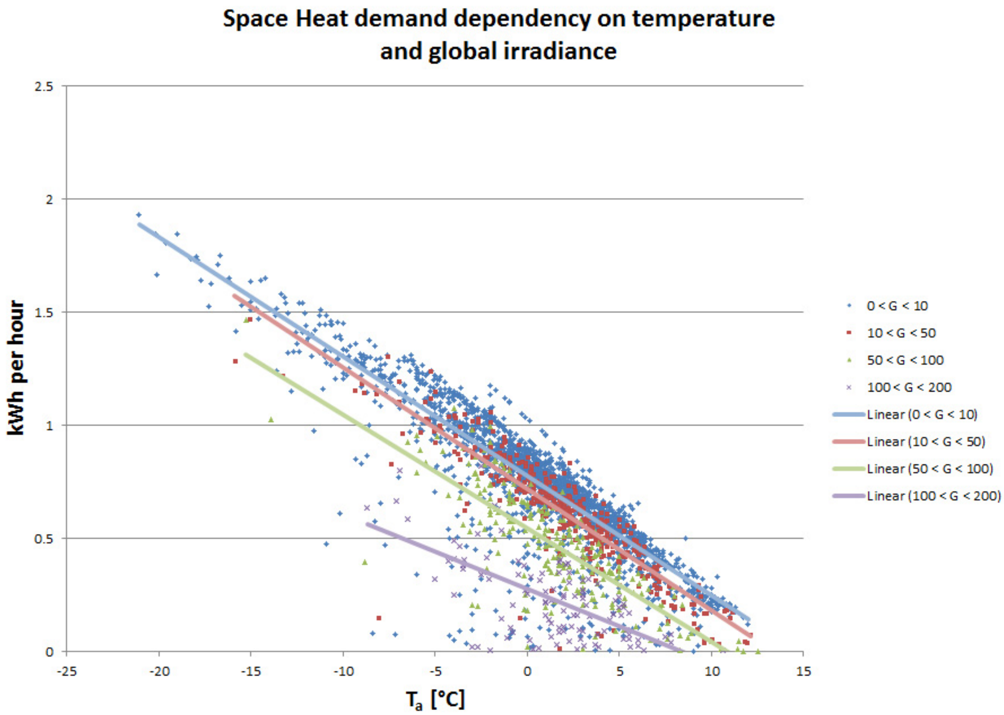

Fig. 4. The space heating demand curves based on a passive house under Danish weather conditions. T_a is the ambient temperature and G is the global irradiance.[5]

2.6. *DHW and space heating demand simulation*

To ensure realistic operation conditions for the solar combi system a domestic hot water demand was simulated. Three times a day hot water from the buffer storage inner tank was discharged. Each discharge was of hot water equivalent to 1.53 kWh. The total draw off was equivalent to 100 liters of water being heated from 10 °C to 50 °C or 4,6 kWh per day.

To simulate the space heating demand a set of demand curves were developed based on simulations of a 130 m^2 passive house using the Danish weather reference year. The passive house standard dictates a total space heating demand of 15 kWh per m^2 per year assuming the weather data of the Danish reference year. Since the passive house had large south facing windows and was very well insulated both the global irradiance and the ambient temperature had an influence on the heat demand. The curves can be seen in figure 4. Using the curves it was possible for the space heating demand simulation to estimate the heat demand based on the current weather.

3. Results

The solar combi system was built in the spring and summer of 2015 and put in operation the 4^{th} of June 2015. Apart from short periods of maintenance the system was operating continuously and data were gathered. As more knowledge of the system behavior was available improvements were made to optimize performance both in terms of system components and software updates. The data analyzed and presented in this paper are from the 4^{th} of June to the 23^{rd} of November. Since this is an ongoing research project the data and conclusions are preliminary and might change with further study of the system.

3.1. Heating PCM modules by solar collectors

One of the main focuses of the experiment was to prove that it is possible to heat the 200 kg of SAT in the modules to sufficiently high temperatures to achieve supercooling. From previous laboratory tests of the modules it was established that a material temperature of 80 °C was necessary. This is well above the melting temperature of SAT of 58 °C and requires the solar collector field to deliver heat while the solar collector inlet temperatures are above 80 °C.

During the test period the modules were heated by the solar collectors to a SAT temperature of 80 °C 53 times. It was possible to reach this temperature in the modules until the middle of October. The maximum charge power to the modules was 11.4 kW averaged over a one hour period which is the energy equivalent of 2.5 days of domestic hot water consumption. This was achieved the 30th of September with a total irradiation of 879 W/m^2 which equates to a solar collector including pipe losses efficiency of 58%, as calculated by equation 1, with an average collector inlet temperature of 89.2 °C.

$$\eta = \frac{\dot{V}_{PCM} \cdot \rho_w \cdot c_{p,w} \cdot \Delta T}{G_t \cdot A} \tag{1}$$

Where η is the efficiency of the solar collector including pipe losses when charging the PCM storage. G_t is the total irradiance on the collectors and A is the collector aperture area. $\dot{V}_{PCM}$ is the flow of heat transfer fluid, water, in the PCM storage, ρ_w is the density of water, $c_{p,w}$ is the specific heat capacity of water and ΔT is the temperature difference of the inlet and outlet of the PCM storage.

In general the system was able to charge the PCM heat storage with power in excess of 10 kW even with high inlet temperatures to the solar collector array. An example of charging and discharging power over a one month period can be seen in figure 5.

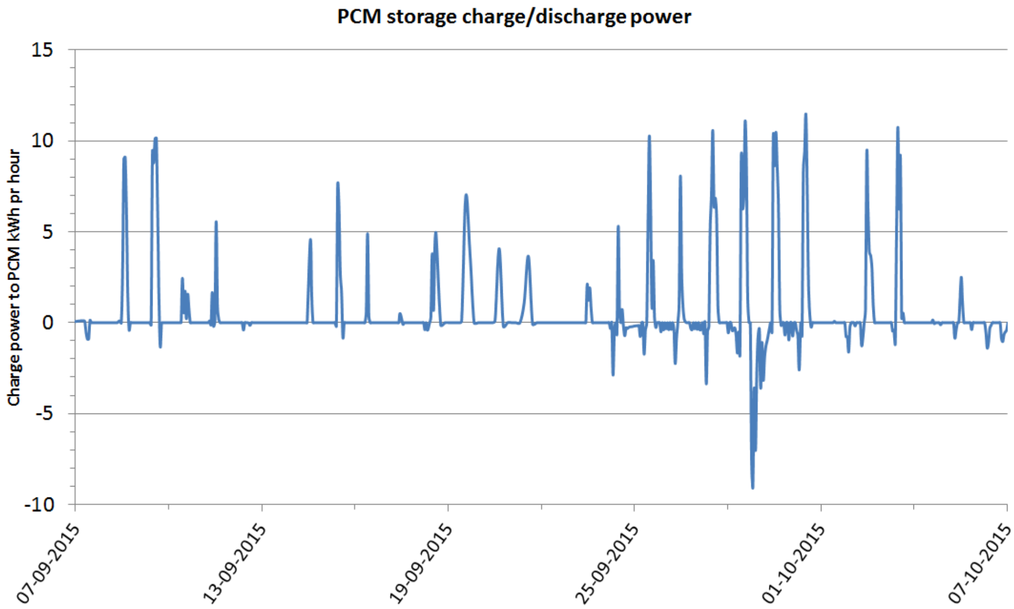

Fig. 5. The charge and discharge power of the PCM modules from 7th of September to the 7th of October 2015.

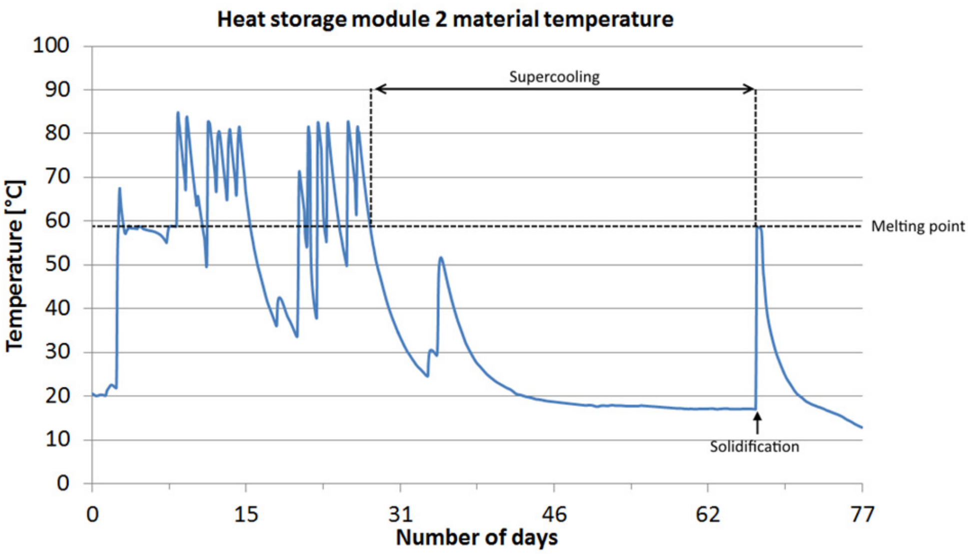

Fig. 6. The charge and supercooling behaviour of an individual PCM module, module 2, showing a supercooling period of 39 days.

3.2. Discharging heat from the PCM modules to the buffer tank

When the system detected a low buffer tank temperature and there was no heat available from the solar collectors, heat from the PCM storage was discharged to the buffer tank. This was done throughout the test period and a total of 135 kWh was discharged from the PCM storage to the buffer storage. This was equivalent to the domestic hot water consumption of 29.3 days.

One of the core concepts of the PCM storage using SAT is its ability to supercool. This enabled the system to charge the modules when there was excess heat and then let the modules cool to ambient temperature without the SAT solidifying, preserving the heat of fusion. As part of the test regime one module was heated with solar heat, passively cooled to ambient temperature and left in a supercooled state for more than a month. A seed crystal was introduced to the SAT in the module which then solidified and the temperature measured inside the material increased from 17.1 °C to 58.5 °C. The heat of fusion was then discharged to the buffer tank. The temperature history of the module can be seen in figure 6 where a period of 39 days of supercooling was followed by a solidification event and 11 kWh of heat was discharged to the buffer tank.

Previous laboratory tests with the same modules have shown that supercooling SAT has the potential to store energy for much longer periods and further tests will determine if this is also true for the large scale SAT modules described in this paper.[3]

A full description of the energy supplied by the solar collectors to the buffer tank and PCM storage as well as the demands simulated and the system efficiency is not part of the scope of this paper. Research publications with this focus will be published at a later date.

4. Conclusion

As part of the solar combi system test regime the SAT modules were heated by solar heat to a temperature above 80 °C 53 times in the six month test period. The principle of utilizing stable supercooling of a PCM for compact long term heat storage with SAT was confirmed by the tests. It was possible to heat the modules containing approximatly 200 kg of SAT and additives to sufficiently high temperatures to obtain stable supercooling.

The PCM heat storage did contribute with 135 kWh of heat to the buffer tank. After 39 days of remaining in a supercooled state the SAT in a module was solidified intentionally and a total of 11 kWh of heat was discharged to the buffer tank.

Continued tests of the system will show the full potential of PCM long term heat storages based on SAT in solar combi systems. The core concepts of super cooling and discharge of heat from the PCM to a buffer storage tank have been shown.

Acknowledgements

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