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# Laboratory test of a cylindrical heat storage module with water and sodium acetate trihydrate

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## Abstract

Cylindrical heat storage modules with internal heat exchangers have been tested in a laboratory. The modules were filled with water and sodium acetate trihydrate with additives. The testing focused on the heat content of the storage material and the heat exchange capacity rate during charge of the module. For the tests with the phase change materials, the focus was furthermore on the stability of supercooling and cycling stability. Testing the module with sodium acetate trihydrate and 6.4% extra water showed that phase separation increased and the heat released after solidification of supercooled phase change material was reduced over 17 test cycles. The heat released after solidification of the supercooled sodium acetate trihydrate with thickening agent and graphite was stable over the test cycles. Stable supercooling was obtained in 7 out of 17 test cycles with the module with sodium acetate trihydrate with extra water and in 6 out of 35 test cycles for the module with thickening agent.

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*Keywords:* Heat storage; Phase change material; Sodium acetate trihydrate; supercooling.

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## 1. Introduction

Thermal energy storage is needed to match the intermitted supply of solar energy with varying demands. To improve the volumetric storage capacity compared to sensible heat storage, latent heat storage technologies can be used. Sodium acetate trihydrate (SAT) is an incongruently melting salt hydrate with a latent heat of fusion of 264 kJ/kg at a melting temperature of 58 °C [1]. These thermal properties make it a suitable candidate material to

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integrate with solar heating systems, space heating and domestic hot water preparation. Furthermore, SAT has the ability to cool down far below its melting point without solidifying. Letting the SAT remain in this supercooled state in temperature equilibrium with the ambient allows for a partly loss free storage when the latent heat of fusion is stored at ambient temperature. When a heating demand arises, solidification of the supercooled SAT can be initiated and the latent heat discharged. This principle makes compact seasonal heat storage possible [2, 3].

## 2. Laboratory testing

Two heat storage modules with mixtures based on SAT were tested in the laboratory. The aim was to investigate the functionality of the storage design including utilization of the principle of stable supercooling. The heat charged to and discharged from the modules was measured based on flow rates and temperatures. The heat loss coefficients of the modules were experimentally determined and the heat contents of the stores, the heat exchange capacity rates during charge, the discharge power and temperatures were determined and compared for the different storage mediums.

### 2.1. Heat storage design

The storage modules were designed as cylinders in stainless steel with a height of 150 cm and a diameter of 30 cm. A layer of EPP insulation covered the cylinders making the total height of the heat storages 160 cm and the diameter 38 cm. The internal heat exchanger consisted of 16 stainless steel pipes located in a circular formation in the length of the cylinder with thin aluminum plates attached as fins to increase the heat transfer area. Manifolds with inlets and outlets were located on the top and bottom of the cylinders. The distance between the aluminum plates were approximately 0.5 - 1 cm.

### 2.2. Storage materials

The storage was initially tested with water as the storage medium as a reference since it has traditionally been used for short term storage. Sodium acetate trihydrate melts incongruently and its storage potential will be reduced over repeated test cycles due to the phase separation if this is not avoided. Additives such as extra water or thickening agents have been suggested for solving this problem [4, 5]. Adding graphite to the SAT mixture can improve the heat transfer without compromising the stability of the supercooling [6, 7]. The heat storages were tested with three different storage mediums:

- 91 kg water
- 109 kg SAT mixed with 7 kg of extra water
- 111 kg SAT mixed with 580 g Xanthan rubber and 5 kg of fine graphite powder.

Given the respective densities of water and SAT, the modules were filled approximately 90% of the total volume for all storage materials. This was to allow for the expansion and contraction of the storage mediums during heating and cooling.

### 2.3. Heat storage test setup

The air volume in the top of the cylinder was either connected to an external expansion vessel via a tube to allow for expansion and contraction of the storage mediums inside the module with minimal pressure built-up. Alternatively, an air filter was installed instead of the expansion in the top of the tank to allow for the density changes without pressure built up while reducing the risk of particles to enter the chamber and disturb the stability of the supercooling.

The heat storage modules were connected via a pipe loop with water as the heat transfer fluid to an electric heating element and a central cooling unit. During charge and discharge the flow direction was from bottom to top.

For charging the inlet temperature of the heat transfer fluid was approximately 90 °C and during discharge the inlet temperature was approximately 20 °C.

#### 2.4. Calculations

The powers  $\dot{Q}$  for charge and discharge of the storage were determined by:

$$\dot{Q} = \dot{V} \cdot c_p \cdot \rho \cdot (T_i - T_o) \quad (1)$$

where,  $T_i$  is the inlet temperature,  $T_o$  is the outlet temperature,  $\dot{V}$  is the volume flow rate of the heat transfer fluid measured at the inlet,  $c_p$  is the specific heat capacity of the heat transfer fluid,  $\rho$  is the density of the heat transfer fluid.

The heat loss coefficients of the storages were determined experimentally by heating the modules to stable temperatures for a period where no additional energy was stored in the heat stores. The energy balance of the heat storage was then used to determine the heat loss coefficient. In this way a simplified heat loss coefficient with a constant value was determined by:

$$H_{loss} = \frac{\dot{Q}}{(T_s - T_{amb})} \quad (2)$$

where  $T_s$  is the mean storage temperature and  $T_{amb}$  is the ambient temperature. The heat loss coefficient of the storage module was used when calculating heat content of the storage based on the measured data. The change of heat content in the storage module over a specific time period was determined by:

$$E(t) = \int_0^t (\dot{Q} - H_{loss}(T_s - T_{amb})) dt \quad (3)$$

The heat exchange capacity rate (HXCR) indicates how fast heat is be transferred between the heat transfer fluid and the storage. A high HXCR is desired for charge and discharge of the storage with a high power. The HXCR was expressed by the following equation:

$$HXCR = \dot{V} \cdot c_p \cdot \rho \cdot \ln \left( \frac{T_i - T_s}{T_o - T_s} \right) \quad (4)$$

### 3. Results

The heat content and the storage temperature of a selected test cycle of the module filled with SAT and extra water is shown in Fig 1. The heat loss coefficient was experimentally determined by equation (2) to  $H_{loss} = 1.8$  W/K. The heat content was calculated by equation (3). For this test cycle the module was kept at a temperature of 90 °C for about 24 hours after which the sensible heat of the module was discharged. This left the module in supercooled state. After two days at supercooled state, the solidification of the PCM was initiated and the latent heat of fusion released. The temperature of the PCM increased to close to the melting temperature of 58 °C and the last heat was discharged.

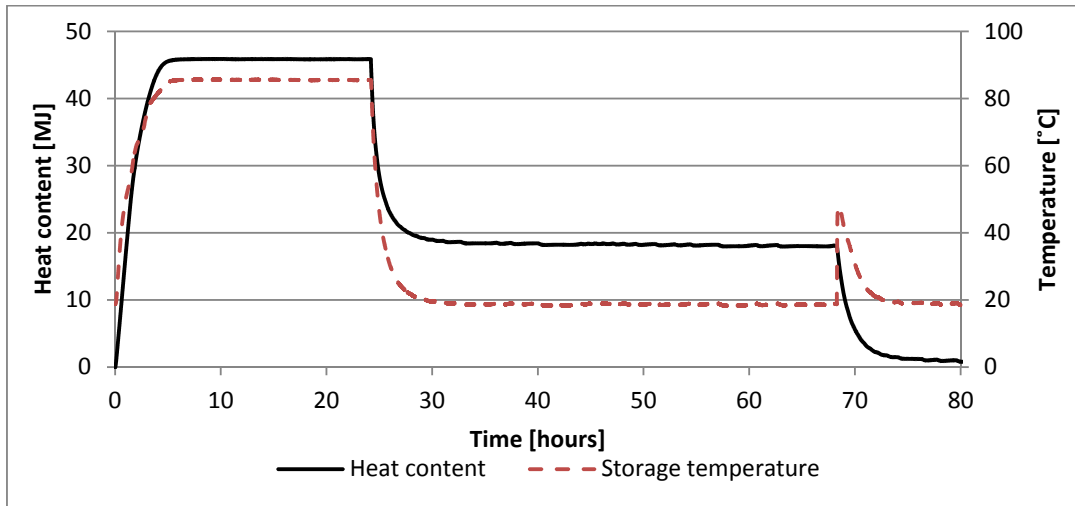


Fig. 1. Heat content and storage temperature of one test cycle of storage with SAT and extra water.

In Table 1 the heat contents of the modules tested with water, SAT and extra water and SAT with Xanthan rubber are compared for the applied temperature ranges.

Table 1. Temperature intervals and measured heat contents for selected test cycles for modules with water and SAT mixtures.

	Water		SAT + water		SAT + Xanthan rubber + graphite	
Heat content	18 - 86 °C	29 MJ	19 - 86 °C	46 MJ	22 - 90 °C	51 MJ
Discharged sensible	82 - 19 °C	26 MJ	86 - 19 °C	28 MJ	91 - 19 °C	29 MJ
Discharged latent			19 - 19 °C	17 MJ	22 - 17 °C	24 MJ

It can be seen that the sensible part of the SAT mixtures was fairly similar to the heat content of the water. Including adjustments for the slightly different temperature intervals for the test cycles with the SAT mixtures, the module with SAT and xanthan rubber contained 9% more heat in the charged state and 30% more heat was discharged after solidification compared to the module with SAT and extra water.

During the 17 test cycles with SAT and extra water, the heat released after solidification from supercooled state dropped from 19 MJ to 16 MJ. This was due to phase separation which was visually observed in the module. Solidification started spontaneously from the bottom in 10 of the 17 test cycles. This was most likely due to cracks or joints at the bottom inside the chamber which could initialize the solidification.

During the test cycling with the module with SAT and Xanthan rubber, the heat discharged after solidification was stable around 24 MJ over 35 test cycles. Supercooling down to ambient temperature was only achieved in 6 test cycles. In the majority of the test cycles where stable supercooling failed, the solidification started spontaneously from the top of the module possibly due to the expansion volume of the tank not working as intended.

The intervals of the HXCR during charge for selected test cycles are listed in Table 2. Charge powers of 6 or 9 kW and flow rates of approximately 7.3 l/min were applied.

Table 2. Heat exchange capacity rates for charge for selected test cycles.

HXCR	Water	SAT + water	SAT + Xanthan rubber + graphite
Charge 9 kW	100-430 W/K	100-220 W/K	
Charge 6 kW		135-235 W/K	50-190 W/K

It can be seen that the HXCR was significantly higher for the module with water compared to the modules with SAT mixtures. This was because heat transfer was dominated by convection in the water from the start. The SAT mixtures were in solid state from the start of the charge and heat transfer was primarily by conduction at this stage. As the SAT mixtures melted, more heat was transferred by convection during charge. The viscosity of the melted SAT and Xanthan rubber mixture was higher compared to the SAT with extra water due to the thickening effect. This caused less convection and finally a lower HXCR in the module with SAT and Xanthan rubber compared to the module with SAT and extra water.

After initializing the solidification in the modules with the SAT mixtures, they were discharged with an inlet temperature of 20-25 °C. The maximum temperature difference between the inlet and outlet during discharge and the peak discharge powers are listed in Table 3.

Table 3. Maximum temperature difference between in and outlet of heat transfer fluid during discharge after solidification for selected test cycles.

Max temperature increase / Peak power	SAT + water	SAT + Xanthan rubber + graphite
Discharge latent heat 2 l/min	29 K / 2.9 kW	30 K / 3.2 kW
Discharge latent heat 5.5 l/min	10 K / 4.1 kW	15 K / 5.3 kW

Higher discharge powers and temperatures were achieved for the module with SAT, Xanthan rubber and graphite compared to the module with SAT and extra water. This was due to higher solidification temperature, higher heat content and a higher thermal conductivity of the SAT, Xanthan rubber and graphite mixture compared to the SAT and extra water mixture.

#### 4. Conclusions

The laboratory tests showed that the heat exchange capacity rate for the modules with SAT mixtures was lower than with water. This was due to less heat transfer by convection. The heat exchange capacity rate of the module with SAT and Xanthan rubber was lower compared to the module filled with SAT and extra water.

Tests of the module with SAT and extra water showed that the energy released after solidification of the supercooled SAT mixture was reduced over a number of test cycles due to phase separation. The heat content in the module filled with SAT and Xanthan was stable and higher compared to the module with SAT and extra water. Higher discharge temperatures and discharge powers were achieved for the module with SAT and Xanthan rubber compared to the module with SAT and extra water.

Stable supercooling to ambient temperatures was achieved in 7 out of 17 test cycles with the module with SAT and extra water. The spontaneous crystallization started from the bottom of the storage module. In the module with SAT and Xanthan rubber stable supercooling was achieved in 6 out of 35 test cycles. Crystallization started mostly from the top of the module.

The research showed that the storage principle works but an effective method for handling the expansion of the SAT which does not compromise the stability of supercooling is yet to be found.

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