



# Experimental investigations on cylindrical latent heat storage units with sodium acetate trihydrate composites utilizing supercooling



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## HIGHLIGHTS

- Thermal energy storage units with supercooled of sodium acetate trihydrate are characterized.
- Heat exchange capacity rates were lower for units with PCM with thickening agents.
- Phase separation of sodium acetate trihydrate was avoided by thickening agent.

## ARTICLE INFO

### Article history:

Received 24 February 2016

Received in revised form 20 May 2016

Accepted 23 May 2016

### Keywords:

Compact thermal energy storage

Latent heat

Phase change material

Sodium acetate trihydrate

Supercooling

## ABSTRACT

Latent heat storage units utilizing stable supercooling of sodium acetate trihydrate (SAT) composites were tested in a laboratory. The stainless steel units were 1.5 m high cylinders with internal heat exchangers of tubes with fins. One unit was tested with 116 kg SAT with 6% extra water. Another unit was tested with 116.3 kg SAT with 0.5% Xanthan rubber as a thickening agent and 4.4% graphite powder. The heat exchange capacity rate during charge was significantly lower for the unit with SAT and Xanthan rubber compared to the unit with SAT and extra water. This was due to less convection in the thickened phase change material after melting. The heat content in the fully charged state and the heat released after solidification of the supercooled SAT mixtures at ambient temperature was higher for the unit with the thickened SAT mixture. The heat discharged after solidification of the supercooled SAT with extra water decreased over repeating charge and discharge cycles while the heat discharged from the SAT with Xanthan rubber remained stable. In both units, the solidification started spontaneously in the majority of the test cycles. This was due to the design of the unit or the method for handling the expansion and contraction of the SAT during charge and discharge.

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## 1. Introduction

Large amounts of energy are used for heating of buildings. A significant part of the energy used to cover these demands comes from fossil fuels. The burning of fossil fuels leads to climate change and other pollution. Clean energy free from greenhouse gas emissions can be produced by renewable resources such as solar. Solar irradiance can be harvested by solar collectors as thermal energy and used for heating purposes. The supply of solar energy is however intermittent and does often not meet demand patterns. Thermal energy storage is therefore needed as parts of solar heating systems to match the intermittent supply of solar energy with varying demands.

Phase change materials (PCM) can be used to improve the volumetric storage capacity of a thermal energy storage compared to a sensible heat storage by utilizing the latent heat of fusion [1–3]. Sodium acetate trihydrate (SAT) is an incongruently melting salt hydrate with a latent heat of fusion of 264 kJ/kg at the melting point of 58 °C [4]. These thermal properties make SAT a suitable material to integrate with solar heating systems, space heating and domestic hot water preparation. Furthermore, melted SAT has the ability to cool down to ambient temperatures without crystallizing [5]. Letting the SAT remain in this supercooled state allows for a partly loss-free storage, when the latent heat of fusion of the SAT is stored in temperature equilibrium with the ambient. Solidification of the supercooled SAT can be initiated when a heat demand arises and the latent heat of fusion is released and used for the heating purpose. This principle of utilizing stable supercooling makes compact seasonal heat storage possible in decentralized systems for example in single family houses [6].

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## Nomenclature

$C_p$	specific heat capacity [kJ/kg K]	$T_{start}$	storage temperature at the start of a cycle [°C]
$C_{tank}$	heat capacity of storage tank material [kJ/K]	$T_{super}$	temperature of the storage with the PCM in supercooled state [°C]
$E_{charge}$	measured heat content after charge [J]	$\dot{V}$	volume flow rate [m <sup>3</sup> /h]
$E_{discharge}$	measured discharged heat [J]	$\rho$	density [kg/m <sup>3</sup> ]
$E_{PCM}$	heat capacity of PCM [kJ/kg]	<i>Abbreviations</i>	
$H_{loss}$	heat loss coefficient [W/K]	SAT	sodium acetate trihydrate
$HXCR$	heat exchange capacity rate [W/K]	SATH2O	mixture of 93.6% SAT and 6.4% water
$m$	mass [kg]	SATXC	mixture of 95.1% SAT, 0.5% Xanthan rubber and 4.4% graphite powder
$\dot{Q}$	charge/discharge power [W]	PCM	phase change material
$t$	time [s]	CMC	carboxymethyl cellulose
$T_{amb}$	ambient temperature [°C]		
$T_i$	inlet temperature [°C]		
$T_{max}$	maximum storage temperature [°C]		
$T_o$	outlet temperature [°C]		
$T_s$	storage mean temperature [°C]		

### 1.1. State of the art

A lot of research has previously been carried out aiming to find solutions for improving the performance of thermal energy storage. López-Navarro et al. did an experimental characterization of a PCM storage tank with paraffin [7]. Novo et al. did a review on large seasonal sensible heat storage [8]. Nkwetta and Haghghat did a review on available technologies including active systems for thermal energy storage with PCMs [9]. Sharif et al. likewise did a review on applications with PCMs for space heating and domestic hot water preparation [10]. None of these reviews included technologies that utilize supercooling of a PCM. Xu et al. [11] and Pinel et al. [12] did reviews on methods and available technologies for seasonal thermal energy storage and briefly touch on the concept of utilizing supercooling of SAT for compact seasonal heat storage. Persson and Westermark did an analysis of the economy of buildings with seasonal thermal energy storage and found that their relative competitiveness was higher when used for passive houses compared to houses with higher heat demands [13]. Colclough and McGrath did life cycle analysis of a low energy dwelling and found that over a long-term perspective, a solar combi-system with seasonal thermal energy storage had the lowest embodied energy and carbon [14].

Dannemand et al. presented in an article a number of practical solutions to barriers and problems for obtaining a functional heat storage based on stable supercooling of SAT [15]. They also describe how this concept can be used for seasonal heat storage of solar thermal energy.

### 1.2. Sodium acetate trihydrate composites

Phase separation is a key problem when using the incongruently melting SAT as a heat storage material. Melted SAT consists of sodium acetate dissolved in water [16]. The solubility of the sodium acetate is too low in the supercooled state to dissolve all the salt in the water from the melted SAT. Undissolved sodium acetate will therefore settle to the bottom of the container. All the potential SAT crystals cannot be formed when the SAT solidifies again due to the physical separation of the segregated sodium acetate at the bottom and the corresponding water in the top of the container [17]. This reduces in practice the latent heat of fusion and the heat storage potential [18]. One suggested solution for solving this problem has been adding extra water to the SAT. In this way all the sodium acetate can be dissolved in water [19]. Adding extra water to the PCM mixture will however reduce the heat storage capacity compared to SATs potential [20].

Another possible solution is adding a thickening agent to the SAT. The precipitated sodium acetate will then stay suspended in the thickened supercooled solution and will not settle to the bottom. In this case the sodium acetate can recombine with the nearby water molecules at crystallization to form SAT [21]. However, the heat transfer in a PCM storage is affected by the convection in the PCM as elucidated by Sun et al. and may be reduced when the viscosity increases [22]. Ryu et al. investigated several thickening agent for different salt hydrates [23]. Several authors found that an SAT composite with carboxymethyl cellulose (CMC) was stable through thermal cycling [24–26]. Meisingset and Grønvold suggested using Xanthan rubber as a thickening agent [21]. All of these investigations were on a small laboratory scale and not tested on a scale representing heat storage applications large enough to meet a heat demand of a single family house.

In laboratory experiments Dannemand et al. characterized the performance of two flat storage units with approximately 200 kg SAT mixtures, one with extra water and another with CMC [27,28]. The tested units had an internal height of the PCM chamber of 5 cm. The low height was to reduce the risk of phase separation. Higher units may result in aggravated phase separation but with fewer design restrictions. They found that the heat content was reduced over repeated charge and discharge cycles for the unit with SAT and extra water but it was stable for the unit with SAT and CMC. They also found that the heat exchange capacity rate was lower in the unit with the thickened SAT mixture.

### 1.3. Heat transfer

The heat transfer of a PCM storage unit is highly affected by the design of the heat exchanger. Different designs were evaluated by Medrano et al [29]. Chiu and Martin investigated numerically and experimentally the performance of a finned heat exchanger heat storage unit [30]. The low thermal conductivity of PCMs is another typical challenge of using PCMs in heat storage [31]. This combined with no heat transfer by convection when the PCM is in solid state and limited heat transfer by convection in a melted PCM with high viscosity, may result in a low heat exchange capacity rate (HXCR) in a PCM storage [32].

It was shown by Dannemand et al. through numerical simulations that the HXCR of a PCM storage had a significant impact on the system performance of a solar combi-system including a PCM storage utilizing supercooling [15].

As the thermal conductivity of the PCM in a store affects the HXCR, improvement of the thermal conductivity of PCMs has been investigated by several researchers. Enhancing the thermal

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