



## Long term thermal energy storage with stable supercooled sodium acetate trihydrate

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1 **Title:** Long term thermal energy storage with stable supercooled sodium acetate trihydrate.

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4 **Abstract**

5 Utilizing stable supercooling of sodium acetate trihydrate makes it possible to store thermal energy partly  
6 loss free. This principle makes seasonal heat storage in compact systems possible. To keep high and stable  
7 energy content and cycling stability phase separation of the storage material must be avoided. This can be  
8 done by the use of the thickening agents carboxymethyl cellulose or xanthan rubber. Stable supercooling  
9 requires that the sodium acetate trihydrate is heated to a temperature somewhat higher than the melting  
10 temperature of 58°C before it cools down. As the phase change material melts it expands and will cause a  
11 pressure built up in a closed chamber which might compromise stability of the supercooling. This can be  
12 avoided by having an air volume above the phase change material connected to an external pressure less  
13 expansion tank. Supercooled sodium acetate trihydrate at 20°C stores up to 230 kJ/kg. TRNSYS simulations  
14 of a solar combi system including a storage with four heat storage modules of each 200 kg of sodium  
15 acetate trihydrate utilizing stable supercooling achieved a solar fraction of 80% for a low energy house in  
16 Danish climatic conditions.

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17 Utilizing the principle of stable supercooling of sodium acetate trihydrate makes it possible to store thermal  
18 energy over long periods of time with minimal thermal losses. To keep a high storage potential the phase  
19 separation of the salt hydrate must be avoided e.g. by use of a thickening agent. Stable supercooling  
20 requires that the sodium acetate trihydrate is heated to a temperature somewhat higher than the melting  
21 temperature of 58°C before it is cooled down. Expansion and contraction of the phase change material in a  
22 closed tank compromises the stability of the supercooling. An expansion device that allows for the phase  
23 change material to expand and contract without pressure changes in a closed chamber makes it possible to  
24 achieve stable supercooling. Initializing the crystallization of the supercooled sodium acetate trihydrate can  
25 be done by cooling the phase change material locally to the maximum level of supercooling or by  
26 mechanically providing a seed crystal. Supercooled sodium acetate trihydrate at 20°C stores up to 230  
27 kJ/kg of thermal energy. The energy discharged is affected by the storage temperature of the supercooled  
28 phase change material before crystallization and the final discharge temperature. Internal cavities are  
29 formed during the contraction of the phase change material when crystallizing decreasing the heat transfer  
30 rate. A thermally conductive liquid that does not mix with the phase change material can be added to fill  
31 the cavities and enhance the heat transfer. Graphite powder can improve the thermal conductivity of the  
32 sodium acetate trihydrate and needs to be kept dispersed evenly in the phase change material by a  
33 thickening agent that is stable at the maximum temperature of the storage during the charging. A TRNSYS  
34 simulation of a solar thermal combi system including a storage utilizing stable supercooling of sodium  
35 acetate trihydrate elucidates the system size to achieve 80 % solar fraction of the low energy house in  
36 Danish climatic conditions.

37 **Keywords:** Compact seasonal heat storage; long term thermal energy storage; phase change material;  
38 PCM; supercooling, sodium acetate trihydrate.

## 39 1. Introduction:

40 Space heating of buildings and domestic hot water supply account for a large part of our energy use. Solar  
41 energy is more abundant in summer than in winter periods when heating demands are much larger.  
42 Thermal energy storage technologies are therefore needed to match the intermittent supply of solar  
43 energy with varying heating demands if solar heating systems should fully cover our heat demand.  
44 Currently available heat storage systems that use water as the storage medium work well but mainly for  
45 short term storage, as their continuous heat losses limit the storage period. With a very large water  
46 storage, it is possible to store heat enough for a whole winter for a single family house but implementation  
47 is limited due to practicalities. For long storage periods in compact storages alternative technologies are  
48 needed. For this study long term storage is considered as biannually or longer periods which are required  
49 for seasonal heat storage.

50 Heat storages utilising latent heat of fusion of a phase change material (PCM) has been suggested for  
51 improving the performance compared to heat storage of sensible heat by several authors. Sharma and  
52 Sagara made an extensive review on latent heat storage materials and systems [1]. Nkwetta et al. did a  
53 review on the experimental and theoretical studies including PCMs in storages and solar collectors [2].  
54 Sharif et al. also did a review on application of PCM for hot water and heating system [3]. Sole et al. showed  
55 that including PCM in a water storage can improve its performance [4]. Wada et al. investigated several  
56 promising mixtures for solar energy storage [5]. Canbazoglu et al. investigated how hydrated salts can  
57 enhance the thermal energy storage performance of solar water heating systems [6]. Nagano et al. did  
58 experimental investigations in a latent heat storage considered for waste heat utilization and found that  
59 available enthalpy was more than double compared to a water storage [7]. López-Navarro et al. presented  
60 the design of a latent cold storage with a paraffin and characterized its performance [8]. Arce et al.  
61 elucidates how thermal energy storage can reduce energy consumptions with theoretical calculations [9].  
62 Abhat introduces some fundamental considerations for both sensible and latent heat storages related to  
63 material properties and storage design [10].

64 Supercooling, subcooling or undercooling is when a phase change material in liquid state cools down below  
65 its melting point without solidifying; leaving it in a metastable state where the latent heat of fusion is not  
66 released. In latent heat storage supercooling has traditionally been seen as an undesired effect that had to  
67 be avoided as it prevented the heat of fusion from being released when the melting point of the storage  
68 material was reached during the discharge process [11]. This can be done by using various nucleation  
69 agents such as Aluminium Nitride Nanoparticles [12] or various salts [13]. The idea of utilizing supercooled  
70 salt hydrates for long term storage has however been known since the late 1920s [14] and pocket-sized  
71 heat packs storing heat in supercooled sodium acetate trihydrate were patented in 1978 [15]. This principle  
72 makes long term thermal energy storage possible by letting the melted salt hydrate remain in supercooled  
73 state at ambient temperature in the storage period. Once the heat is needed the solidification of the  
74 supercooled solution is triggered and the latent heat of fusion is released as it crystalizes. Investigations  
75 have previously shown that there is a potential in utilizing stable supercooling as a storage technique.  
76 Hirano and Saitoh showed by numerical simulations that latent heat storages utilizing supercooling have  
77 higher efficiencies than latent heat storages not utilizing supercooling and that the efficiency increases with  
78 longer storage periods [16] and is effected by the operating temperature [17]. The same authors tested a  
79 storage unit utilizing supercooling of 36-39 kg PCM [18]. Sandnes and Rekstad made measurement of  
80 energy released from supercooled samples of salt hydrates and gives recommendation for storage design

81 [\[19\]. Barrett and Best showed that some PCM mixtures can remain in supercooled state well below its](#)  
82 [melting point \[20\]\[18\].](#)

83 Sodium acetate trihydrate has a melting point of 58°C and a relatively high heat of fusion of 264 kJ/kg [21],  
84 supercool consistently down to temperatures well below 0°C ~~[20]~~[22]. [Rogerson and Cardoso investigated](#)  
85 [the relation between nucleation pressure and temperature and found via experiments that sodium acetate](#)  
86 [trihydrate spontaneously crystallizes at -14°C or lower \[23\]. Wei and Ohsasa investigated supercooling and](#)  
87 [solidification of sodium acetate and found that there may be a link between the time and level of heating](#)  
88 [above the melting point and the stability of the supercooling \[24\]. Wada also reports that SAT crystallizes at](#)  
89 [a temperature of -30°C or below \[25\].](#) When considering the application of space heating and domestic  
90 hot water preparation and solar collectors as the heat source, sodium acetate trihydrate has suitable  
91 thermal properties as storage material for long term heat storage [26].

92 Well-functioning ~~large-scale applications- heat storage prototypes~~ utilizing supercooled PCM ~~for which can~~  
93 ~~serve as seasonal heat storage for single family houses long-term storage~~ have not ~~yet~~ been reported. The  
94 primary barriers to achieve an operating storage based on stable supercooling of sodium acetate trihydrate  
95 are listed in this article along with proposed solutions. Suggested solutions are based on a series of  
96 laboratory experiments in small scale and on prototype storage modules. The theoretical storage potential  
97 for sodium acetate trihydrate is calculated based on a simple theory of specific heat capacities and latent  
98 heat of fusion of the PCM. A TRNSYS model simulating a solar combi system including a PCM storage  
99 utilizing stable supercooling of sodium acetate trihydrate covering the heat demand for a passive house in  
100 Danish climatic conditions elucidates the potential for the storage concept.

## 101 2. Barriers, problems and solutions

102 [To achieve a reliable operating heat storage utilizing the principle of stable supercooling of sodium acetate](#)  
103 [trihydrate a number of problems need to be considered and solved. Problems are phase separation;](#)  
104 [expansion and contraction of the PCM during melting and solidifying, stable supercooling, heat transfer to](#)  
105 [and from the PCM and triggering the crystallization. In small sample sizes in closed bottles or jars the](#)  
106 [supercooling of sodium acetate trihydrate is usually reliable every time. When scaling up to larger sizes that](#)  
107 [are required to accommodate heating of buildings a number of problems occur. Dimensioning systems and](#)  
108 [storage sizes require stability of the performance of the PCM in every case.](#) A series of small scale test with  
109 sample sizes of 200-500 g in glass jars and testing of prototype storages containing PCM masses of 100-220  
110 ~~kg kg~~ has led to the following focus points. ~~These points have to be considered when designing a thermal~~  
111 ~~energy storage based on stable supercooling of sodium acetate trihydrate have been carried out in order to~~  
112 ~~find solutions for these problems.~~

### 113 2.1 Phase separation

114 Sodium acetate trihydrate is an incongruently melting salt hydrate and will suffer from phase separation  
115 especially over repeated heating and cooling cycles. This will reduce the ~~heat~~ storage capacity as the energy  
116 released after crystallization of a supercooled sample is reduced when anhydrate sodium acetate  
117 segregates and settles to the bottom of the container so that the reformation of the trihydrate crystal is  
118 prevented [as mentioned by Kimura \[13\] and Lane \[14\]. Furbo and Svendsen did extensive experimental](#)  
119 [testing of storages with salt hydrates \[27\], \[28\]. They suggest that A](#)adding extra water to the salt hydrate

120 so the salt water mixture composition is always at a point where all salt is dissolved in the water when it is  
121 in liquid and supercooled state as a solution. This solution does however reduce the energy density of the  
122 storage [as shown by Araki \[28\]\[29\]. Also the melting temperature of the sodium acetate water mixtures will](#)  
123 [drop with increasing water content which may reduce the performance of the storage](#)[30]. The extra water  
124 principle requires soft mixing of the salt water mixture to avoid phase separation which can possibly be  
125 achieved by the convection during heating, depending on the storage and heat exchanger design. However,  
126 as the phase separation happens mainly in the supercooled state before crystallization is triggered, there  
127 will still be a loss of latent heat of fusion when using the extra water principle for long term thermal energy  
128 storage with supercooling of sodium acetate trihydrate, if the mixing is not applied in another way.

129 Another method to solve the problem with phase separation is to add a thickening agent to the salt hydrate  
130 to keep the segregated salt from settling to the bottom of the container. Several additives such as carboxyl  
131 methyl cellulose (CMC) and Xanthan rubber have been researched previously. [Hu worked with CMC](#) [12].  
132 [Lane reports on some early research in search for cycling stable thickeners](#) [14]. [Cabeza et al. found starch](#)  
133 [and bentonite to be an appropriate thickener for sodium acetate trihydrate. Also Cellulose was tested but](#)  
134 [showed not to be stable above 65 °C](#) [31]. [Wada et al. reports improvement of cycling stability of sodium](#)  
135 [acetate trihydrate when thickened with a mixture including polyvinyl alcohol](#) [32]. [Ryu et al. tested a super](#)  
136 [absorbent polymer and CMC as thickeners and found them effective](#) [33]. [Garay Ramirez et al. reports that](#)  
137 [a mixture of polymers of CMC and Silica Gel reduce phase separation](#) [34].

138 Requirements for the thickening agent are inherently that it is stable over the temperature range of which  
139 the storage operates and the life time of the storage. The drawback of using thickening agents can be  
140 reduced storage density and reduced convection of the melted PCM in the storage, which will reduce the  
141 heat exchange capacity rate in the PCM during the charging process. In small scale tests 200 g samples  
142 were heated to 90 °C in an oven until fully melted and let to passively cool to room temperature. A mixture  
143 of sodium acetate trihydrate and 1 wt% of CMC or 0.5 wt% for Xanthan rubber well mixed into the PCM has  
144 in small scale test shown to be sufficient to change the viscosity enough to keep anhydrate crystals  
145 suspended in the supercooled solution. Thickening agents may have viscosity changing ability varying over  
146 temperatures. To solve the phase separation problem with a thickening agent, it must be able to keep  
147 segregated salt suspended in ~~in~~ the supercooled state, not necessarily in the hot melted state where all salt  
148 is dissolved in the water.

## 149 **2.2 Density changeExpansion of the PCM**

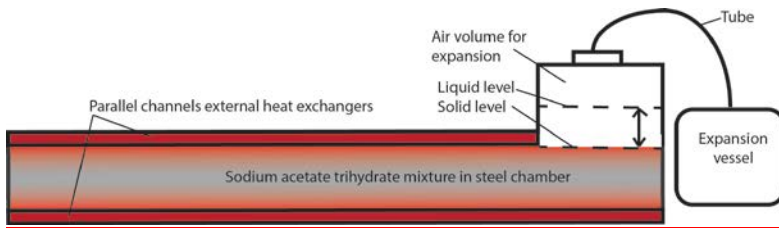
150 With a density of 1,280 kg/m<sup>3</sup> [26] [35] of the liquid sodium acetate trihydrate and 1,450 kg/m<sup>3</sup> of the solid,  
151 a volume difference of more than 10% has to be considered when designing the storage tanks. One  
152 problem related to this expansion is the strains it put on the storage tank during the heating and cooling  
153 cycling. The tank material should be able to withstand the pressure changes and deformations over the  
154 lifetime of the storage if this is not solved in another way. Testing of a prototype module in steel containing  
155 100 kg sodium acetate trihydrate showed a pressure difference of 1.2 bars in the PCM chamber between  
156 the crystalized state at room temperature and the fully melted state at 90 °C.

157 A soft container for the PCM could be a solution if the container material can remain flexible over a life  
158 time of the storage. Also a flexibility of the connection for the storage may possibly be required. A rigid  
159 storage design with an expansion device that allows for the expansion and contraction of the PCM without  
160 pressure built up can eliminate the problems with changing strains in the storage tank material and possibly

161 fatigue over time. In such system a fluid or gas can work as the medium going in and out of the expansion  
162 while the PCM stays in the primary chamber. [The principle of how the expansion issue was solved for the](#)  
163 [prototype testing is illustrated in Figure 1 where an expansion vessel without pre-pressure is connected to](#)  
164 [an air volume above the PCM.](#)

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165  
166 [Figure 1. Principle of heat storage module with expansion vessel to solve expansion of the PCM.](#)

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### 167 2.3 Supercooling and cycling stability

168 To achieve supercooling of the sodium acetate trihydrate it is necessary that all crystals of the bulk are  
169 melted so that it will not crystallise as it cools down. There appears to be a link between the level of  
170 heating above the melting point and the stability of supercooling [as investigated by Wei \[24\] and Wada\[36\]](#).  
171 [This was also investigated by Jin \[37\] who found that heating 8 g sodium acetate trihydrate in a test tube to](#)  
172 [62 °C for 80 minutes would result in no crystallization when it was cooled to ambient temperatures. There](#)  
173 [was no information if the samples crystallized after some time. Our investigations have shown that for](#)  
174 [Both small scale tests and prototype module tests showed a temperature of around 20 K above melting](#)  
175 [point in the entire volume helps to achieve stable supercooling over time.](#) When the ever-present  
176 impurities in the salt hydrate work as nucleation agents, large PCM volumes may show reduced stability of  
177 supercooling, as the chance of a spontaneous nucleation caused by an impurity increases with the volume  
178 [38].

179 Heating the salt hydrate to a high temperature will cause some evaporation of the water; therefore a  
180 closed container with no loss of water through the tank material over the lifetime of the storage unit is  
181 essential to avoid changing the composition of the PCM. As the metastable state of the supercooled salt  
182 hydrate could easily be interrupted by external influences, a closed container is inherently more stable.  
183 Diffusion of the heat transfer fluid from the heat exchanger into the PCM should be avoided. When  
184 considering the choice of tank material, corrosion and chemical reactions between the salt and the tank  
185 material must be considered. Steel and stainless steel in combination with sodium acetate trihydrate has  
186 been shown to be stable over long periods [as shown by Furbo et al. \[27\]\[28\]. Cabeza et al investigated](#)  
187 [corrosion of metals immersed in salt hydrates and also recommends sodium acetate trihydrate in](#)  
188 [combination with steel and stainless steel \[39\].](#)

189 If using rigid constructions such as steel the density change between the cold solid and the warm liquid salt  
190 hydrate must be considered, as the volume change of the PCM in a closed container can cause pressure  
191 changes and deformations of the tank. Just as bending a metal disk with cracks works as a triggering  
192 mechanism for the pocket sized heat packs by creating a local high pressure [40], small cracks on the inside  
193 of the PCM chamber can in combination with pressure changes and deformations work as an uncontrolled  
194 activation mechanism e.g. at joints or welds [41][42]. So if the storage tanks material is of rigid material

195 operating it with constant pressure will provide better stability of the supercooling. Coating of inner  
196 surfaces to eliminate cracks or creating a softer inner surface may be a solution for rigid materials and at  
197 cracks and joints.

## 198 **2.4 Effective heat transfer from PCM to heat transfer fluid**

199 The volume reduction that takes place in sodium acetate trihydrate when changing from the liquid to the  
200 solid phase will form cavities inside the tank. These cavities will reduce the thermal conduction of the bulk  
201 PCM and heat exchange capacity rate between the PCM and the heat transfer fluid of the heat exchangers  
202 in a rigid storage [21][43]. Depending on the heat exchanger design these cavities could be a significant  
203 resistance in heat transfer as the cavities work as thermal resistances. Designing a soft container where the  
204 heat exchangers move along with the expansion and contraction of the PCM can be a solution but this  
205 requires a lot of the tank material in terms of flexibility and lifetime.

206 Another well-known problem of heat transfer in phase change materials is their low thermal conductivity  
207 [44]. To increase the heat transfer and the charge and discharge power of PCM storages, the thermal  
208 conductivity of the PCM has been sought increased by adding high conducting material such as graphite  
209 powder, expanded graphite or fibres to the PCM with good results. [Heinz showed that adding graphite to a  
210 sodium acetate mixture will reduce the internal temperature difference in a sample especially during  
211 heating](#) [45]. [Li et al. made investigations of the effect on adding expanded graphite to sodium acetate  
212 trihydrate](#) [46]. [Frusteri et al. showed that adding about 8% by volume graphite fibres can increase the  
213 thermal conductivity of a composite PCM by a factor of 4](#) [47]. [Shin et al. investigated thermal properties of  
214 sodium acetate trihydrate mixed with expanded graphite and CMC](#) [48]. [Cabeza et al. investigated heat  
215 transfer enhancement in PCM thermal energy storages and found that a graphite matrix was very effective  
216 for heat flux enhancement](#) [49]. [Nkwette did numerical investigations showing the effect of having PCM  
217 integrated in a hot water storage. One of the investigated PCMs was sodium acetate trihydrate with 10%  
218 graphite](#) [50]. A thickening agent that is stable for the operating temperature range which may be as high  
219 as up to 95 °C is required to keep the graphite powder dispersed and evenly distributed in the PCM mixture  
220 and avoiding that the graphite powder segregates. Test with 300 g samples of sodium acetate trihydrate  
221 and fine graphite powder with up to 4% CMC have shown that at a temperature of 90 °C the thickening  
222 effect of the CMC is reduced and the graphite powder settles to the bottom. Samples with Xanthan rubber  
223 has shown to be stable in temperatures up to 90 °C.

224 When operating with supercooling and the rapid crystallization happening from supercooled state, the PCM  
225 may not contract in a uniform way and therefore cavities inside the PCM could form which would further  
226 enhance the problem of low conduction of the PCM. A high conductive liquid possibly oil that does not mix  
227 with the PCM and with a lower density so it floats on top when the PCM is in liquid state could work as an  
228 enhancer for the heat transfer. It could fill the cavities in the PCM and between the PCM and the heat  
229 exchanger. This would lead to a higher effective heat transfer when the PCM solidifies and contracts. This  
230 heat transfer liquid could possibly be considered when designing the expansion device. When the PCM is  
231 heated the oil can be pushed out to the expansion volume of the module.

232 With the low thermal conductivity of the PCM and no convection in the solid phase, the heat exchangers  
233 has to be designed to have good heat transfer, possibly by having large heat transfer areas short distances

234 to the PCM. When designing the heat exchanger the requirements for a minimum temperature in all parts  
235 of the PCM to obtain supercooling should be considered.

## 236 2.5 Triggering the crystallization

237 As the entire volume will solidify once the crystallization is started, it is desirable to divide the storage unit  
238 into a number of separate modules that can be operated individually. The size and number of modules  
239 would depend on the application into which it is integrated and an economic evaluation.

240 The crystallization and release of the heat of fusion from the supercooled sodium acetate trihydrate is  
241 initialised when the first seed crystal of a certain size is present in the solution. From the point of activation  
242 the crystallization will spread to the entire volume and the temperature will rise to close to the melting  
243 point of 58°C [38]. Supplying the seed crystal to trigger the crystallization in a reliable and controllable way  
244 is essential for such a system. Ultra-sonic sound has been tried and found reliable as an activation  
245 mechanism [51]. The metallic disc of the pocket sized heat packs also works reliably but needs moving parts  
246 submerged in the solution and therefore introduce a risk of uncontrollable activation. Mechanically  
247 providing a crystal to the supercooled solution might also be a viable solution. Lastly, it has been shown  
248 that cooling supercooled sodium acetate trihydrate to a low temperature will eventually cause  
249 crystallization of the supercooled solution [22]-[24]. Experiments have shown that 100 g samples of sodium  
250 acetate trihydrate can stay supercooled down to temperatures of -15°C to -25°C before it crystallizes.  
251 Solutions where cooling is used to trigger the formation of the seed crystal could be made using peltier  
252 elements or cooling by the evaporation of liquid CO<sub>2</sub> [24] [22]. One benefit of the cooling method is that  
253 there are no moving parts inside the PCM chamber and that reduces the risk of spontaneous crystallization.  
254 Evaporating liquid CO<sub>2</sub> under pressure has a large cooling power and can be done through the tank wall  
255 from the outside of the tank. The loss of thermal energy by cooling can be considered negligible if just a  
256 tiny part of the PCM is cooled by a high cooling power. Cooling with CO<sub>2</sub> has been a reliable activation  
257 technique in the prototype testing.

## 258 3. Theoretical calculations:

259 The theoretical energy content of the sodium acetate trihydrate is determined by the specific heat capacity  
260 of the solid and liquid phases as well as the latent heat of fusion. The following calculations assume an  
261 ideally performing material without losses due to phase separation; without problems related to stability of  
262 the supercooling, expansion of the PCM, heat transfer and triggering the crystallization. If these problems  
263 are not solved or only partly solved the performance will be worse than described. The theory describes the  
264 thermal energy content in a simple way, assuming that the sodium acetate trihydrate mixture behaves as  
265 an ideal compound that changes phase from solid to liquid at a specific melting temperature. In reality the  
266 phase change may happen over a temperature range especially if extra water is added to the salt  
267 hydrate[27]. When the focus is on the stable initial, fully charged, supercooled and discharged state, this  
268 simple theory provides a sufficient basis for estimation of energy content.

### 269 3.1 Material storage potential

270 The following equations show the theoretical change of thermal energy in the heat storage module for a  
271 given charge. The equation consists of the sensible heat of the salt hydrate in solid and liquid state, the  
272 latent heat of fusion of the salt hydrate and the sensible heat of the storage module material.



$$E_{charge,theo} = m \cdot ((T_{melt} - T_{start}) \cdot c_p(s) + L_f + (T_{max} - T_{melt}) \cdot c_p(l)) + C_{module} \cdot (T_{max} - T_{start}) \quad (1)$$

where  $m$  is the mass of the PCM,  $T_{melt}$  is the melting temperature of the PCM of 58°C,  $T_{start}$  is the mean storage temperature at the start of the charge,  $c_p(s)$  is the specific heat of the PCM in solid phase,  $c_p(l)$  is the specific heat of the PCM in liquid phase,  $L_f$  is the latent heat of fusion of the PCM,  $C_{module}$  is the heat capacity of the storage module material including the heat transfer fluid in the heat exchangers, and  $T_{max}$  is the mean maximum temperature the heat storage module reaches during a charge.

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When the storage module is discharged from the fully charged state at  $T_{max}$  to a temperature  $T_{supercool}$  without crystallising, just the sensible heat of the module and the liquid sodium acetate mixture is discharged. Assuming the specific heat of the supercooled sodium acetate mixture is the same as the liquid sodium acetate mixture, the discharged energy  $E_{dis}$  can be expressed by:

$$E_{dis,theo} = (m \cdot c_p(l) + C_{module}) \cdot (T_{max} - T_{supercool}) \quad (2)$$

where  $T_{supercool}$  is the storage temperature at supercooled state.

The stored thermal energy at supercooled state can be expressed using Eq. 3. Here the discharged energy expressed in Eq. 2 is subtracted from the charged energy expressed by Eq. 1.

$$E_{supercool,theo} = E_{charge,theo} - E_{dis,theo} \quad (3)$$

If the temperature of the storage module at supercooled state  $T_{supercool}$  and end temperature  $T_{end}$  after the activation and discharge are the same, then the thermal energy stored at supercooled state  $E_{supercool,theo}$  at a temperature  $T_{supercool}$  can be expressed by:

$$E_{supercool,theo} = m \cdot (L_f - (T_{melt} - T_{supercool}) \cdot (c_p(l) - c_p(s))) \quad (4)$$

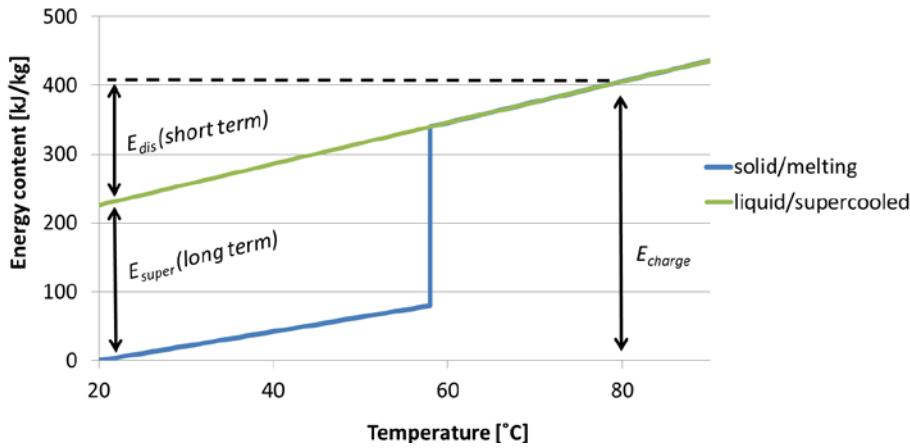
If the storage is discharged to a temperature that is different from that of the supercooled state, the discharged energy is corrected for the difference in sensible heat of the module material and the PCM mixture in solid state.

$$E_{correct,theo} = (T_{supercool} - T_{end}) \cdot (C_{module} + m \cdot c_p(s)) \quad (5)$$

The energy released per unit mass of PCM from activating a supercooled sodium acetate mixture at a specific temperature, corrected for a difference between the final discharge temperature and the temperature of the supercooled PCM mixture before activation is:

$$E_{cont,theo}(T_{supercool}) = \frac{E_{supercool,theo} - E_{correct,theo}}{m} \quad (6)$$

With the specific heat for the solid state sodium acetate trihydrate of 2.1 kJ/kgK and 3.0 kJ/kgK [29] for the liquid state, a latent heat of fusion of 264 kJ/kg at the melting point of 58°C; the energy content per unit of mass at a temperature range relevant for solar heating systems are displayed in [Figure 2](#)[Figure 1](#). The listed specific heat capacities are averaged to a constant at the temperature range. In reality the specific heat capacities vary with temperature [29].



305

306 Figure 2. Principle of long term heat storage utilizing stable supercooling and storage potential for sodium acetate trihydrate.

307 **3.2 System performance by TRNSYS modelling**

308 A TRNSYS model [52] of a solar combi system with a PCM storage was used for a parametric study to  
 309 determine the PCM storage size and solar collector area to obtain a solar fraction of 80% of the yearly heat  
 310 demand for a passive house in Danish climatic conditions. The solar fraction (SF) was defined as

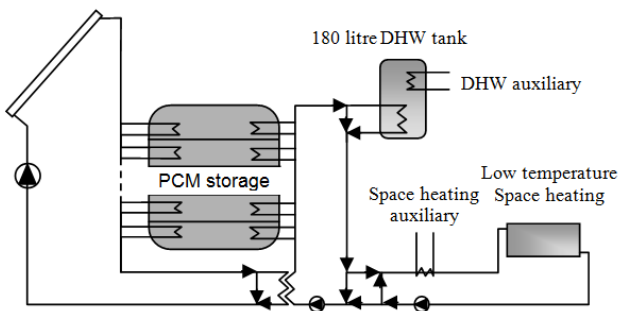
311  $SF = 1 - \frac{Q_{aux}}{Q_{Spa} + Q_{DHW}}$ , where  $Q_{aux}$  is the auxiliary heating for the system,  $Q_{Spa}$  is the energy used for space  
 312 heating and  $Q_{DHW}$  is the energy used for domestic hot water (DHW) preparation. the 80% solar fraction was  
 313 chosen to

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314 A principle diagram of the solar heating system design is shown in Figure 3 ~~Figure-2~~



315

316 Figure 3. Principle diagram of TRNSYS model for solar heating combi system.

317 The system included the PCM storage and a 180 ~~litres-L~~ DHW tank. The DHW tank was required to fulfil the  
 318 power demand related to hot water draw offs, which would be difficult to fulfil with direct discharge of the  
 319 PCM storage. Energy from the solar collectors could either be used for direct charge of the PCM storage or  
 320 transferred to the demand loop through the heat exchanger connecting the solar collector loop and the  
 321 demand loop. Here the energy could either be used for heating of the DHW tank or for space heating. The  
 322 PCM storage was made up of a number of subsections that can be individually controlled with respect to

323 charging, discharging and activation of solidification. The sub sectioning of the PCM storage makes it  
324 possible to activate a small part of the total storage volume to match the demand and saving the rest of the  
325 supercooled sections for later activation. Previous analyses [48][53] have shown that the optimum control  
326 strategy for charging was first to heat up the DHW tank if the forward temperature from the collector was  
327 sufficient. When the DHW tank had reached a temperature of 70°C the PCM storage was thereafter  
328 charged one section at the time until fully melted if the forward temperature from the collector was high  
329 enough. Otherwise the section with the highest temperature that could be further heated was chosen. In  
330 case of space heating demand the necessary forward temperature to the space heating loop was secured  
331 by controlling the flow rate through the DHW heat exchanger if relevant or by discharging a section in the  
332 PCM storage that resulted in the necessary forward flow temperature to the heat exchanger. When  
333 discharging the PCM storage the section that just had the sufficient temperature for covering the actual  
334 demand was chosen. A supercooled section was activated if no liquid or solidified section had the required  
335 temperature level.

336 The PCM storage with sodium acetate trihydrate including the control had been modelled in a TRNSYS type  
337 and a series of parametric studies was carried out in TRNSYS with the system design shown in [Figure](#)  
338 [3Figure-2](#). The solar collectors were flat plate collectors with a start efficiency of 0.82, 1st and 2nd order  
339 heat loss coefficients of 2.44 W/(m<sup>2</sup>·K) and 0.005 W/(m<sup>2</sup>·K<sup>2</sup>)-respectively. The collectors were facing south  
340 with a collector tilt of 75°. The PCM storage and the DHW tank were in the reference case insulated  
341 corresponding to an effective heat loss coefficient of 0.4 W/(m<sup>2</sup>·K). The flow rate in the solar collector loop  
342 was set to 1,800 kg/hr. The heat exchange capacity rate between the PCM in the storage module and the  
343 heat transfer fluid is affected by the design of the heat exchanger and the properties of the PCM.  
344 Simulations with different values for heat exchange capacity rates are made to show how the system size is  
345 related to the heat exchange capacity rate. The heat exchange capacity rate for charge and discharge of the  
346 PCM storage was varied between 200 and 400 W/K in this parameter variation. The volume of the modules  
347 was set to 150 ~~liters~~<sub>L</sub>. The thermal conductivity of the PCM in both solid and liquid state was set to 0.6  
348 W/mK. The daily DHW consumption was set to 99 ~~liters~~<sub>L</sub>/day (33 ~~liters~~<sub>L</sub> draw off at 7:00, 12:00 and 18:00  
349 respectively). The DHW temperature was 50°C and the cold water temperature was 10°C resulting in an  
350 annual DHW energy consumption of approximately 1,677 kWh. The space heating demand was calculated  
351 on hourly basis with the building energy simulation tool, tsbi3 [54] for a low energy house built according to  
352 the passive house standard [55] located in a Danish climate (~ 3,000 degree days; horizontal solar radiation:  
353 ~ 1,020 kWh/m<sup>2</sup>/year). The space heating system was a low temperature system, e.g. floor heating with a  
354 heating demand of 2,008 kWh per year.

355 Previous calculations [56] have been carried out simulating a low energy house with a heating demand of  
356 2,010 kWh per year and an annual DHW consumption of 2,540 kWh. The heat exchange capacity rate for  
357 charge and discharge of the PCM storage was 500 W/K in these calculations. It was shown that it was  
358 possible to achieve a 100% solar fraction for a solar heating system with a 36 m<sup>2</sup> collector area and 6 m<sup>3</sup>  
359 sodium acetate trihydrate divided into 24 subsections. A Module size of 250 ~~litres~~<sub>L</sub> had showed to be the  
360 optimal size in this simulation. For this calculation it was assumed that that heat loss form the storage was  
361 utilized for space heating e.g. by having the storage located inside the building. Overheating of the house in  
362 the summer should be considered in this case. A PCM volume of 10 m<sup>3</sup> was required if the losses were  
363 considers not utilized. The previous study showed that this volume was less than 25% of the required  
364 volume for a water storage to cover 100%.

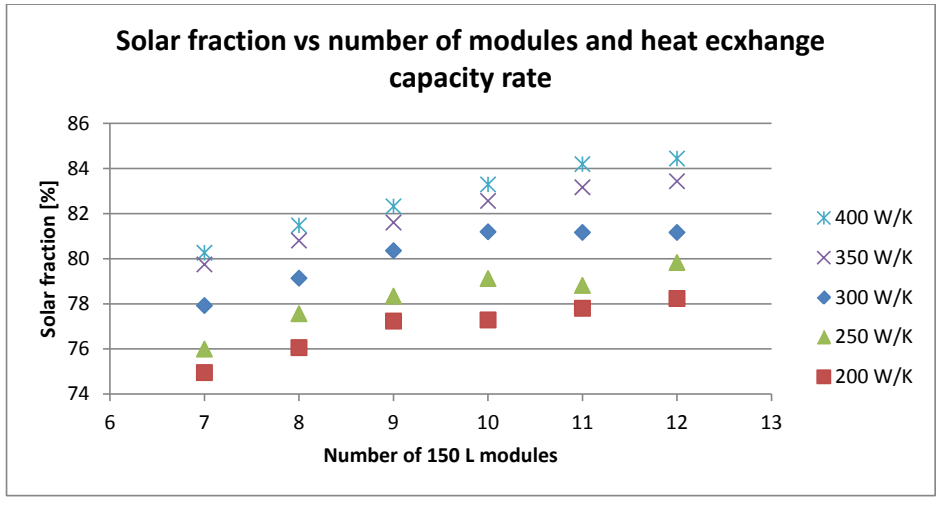
365 **4. Results and discussion:**

366 Based on the theory in section 3.1 it is possible to store 230 kJ/kg of thermal energy in a supercooled  
367 solution of sodium acetate trihydrate at a temperature of 20 °C if it discharged to 20 °C after crystallization.  
368 This assumes no losses due to phase separation. Activating the supercooled PCM at 15 °C and discharging it  
369 to 30 °C will release 194 kJ/kg. Some additional energy will in the case, where storage and final discharge  
370 temperature differs, be lost as it is used to heat up the storage tank material.

371 When operating with PCM in bulk sizes that are needed for storing enough energy for heating building and  
372 long storage periods, the material may act differently compared to small sample sizes. Phenomena like  
373 phase separation and local cavities resulting in thermal resistances may not be obvious in small sample  
374 sizes normally used in material characterization such as T-history and [differential scanning calorimetry](#)  
375 [\(DSC\)](#) measurements. The key material property for making a heat of fusion storage with supercooling is  
376 the latent heat of fusion as this determines the storage capacity. The highest heat of fusion for the sodium  
377 acetate trihydrate is assumed to be of the pure material if phase separation is avoided. Additives such as  
378 thickening agents for stabilizing the PCM or thermal conductivity enhancer will reduce the latent heat of  
379 fusion per unit of mass but may be necessary to have the system perform reliable.

380 **4.1 TRNSYS simulation**

381 The parametric studies carried out were aimed at achieving 80% solar fraction of both DHW and space  
382 heating in a passive house in a Danish climate. The heat exchange capacity rate of a PCM module will  
383 depend on multiple variables such as heat exchanger design and thermal properties of the PCM and heat  
384 transfer fluid as well as operating conditions. Values ranging from 200 W/K to 400 W/K for the heat  
385 exchange capacity rate were included in the parameter variation. From [Figure 4](#)[Figure 3](#) where the solar  
386 collector area of the system was fixed to 36 m<sup>2</sup>, it can be seen that the heat exchange capacity rate of each  
387 module highly affects the solar fraction achieved by the system. With a heat exchange capacity rate of 400  
388 W/K it was possible to reach 80% solar fraction with 7 modules of 150 [liters L](#). If the heat exchange  
389 capacity rate was 250 W/K 12 modules were required to obtain 80% solar fraction.



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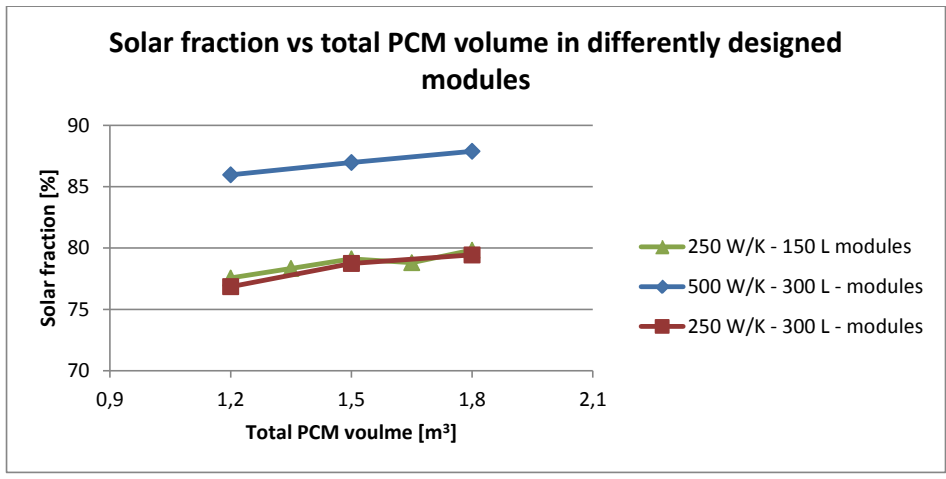
392 **Figure 4. Solar fraction vs number of modules and heat exchange capacity rate for solar combi system with 36 m<sup>2</sup> collector area.**

393 The sizes of the individual modules have also shown to have an effect on the yearly performance of the  
 394 system even if the total PCM volume was kept. Doubling the PCM volume of the modules and assuming the  
 395 heat exchange capacity rate also doubles due to a larger heat exchanger showed to increase the solar  
 396 fraction by 7 percentage points. Doubling the PCM volume without increasing the heat exchange capacity  
 397 rate had almost no effect of the system performance as may be seen in Figure 5. This indicates that there is a  
 398 relation between the operation strategy, energy demand and system design which can be optimized for  
 399 each case.

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401 **Figure 5. Solar fraction vs. total PCM volume in differently designed modules.**

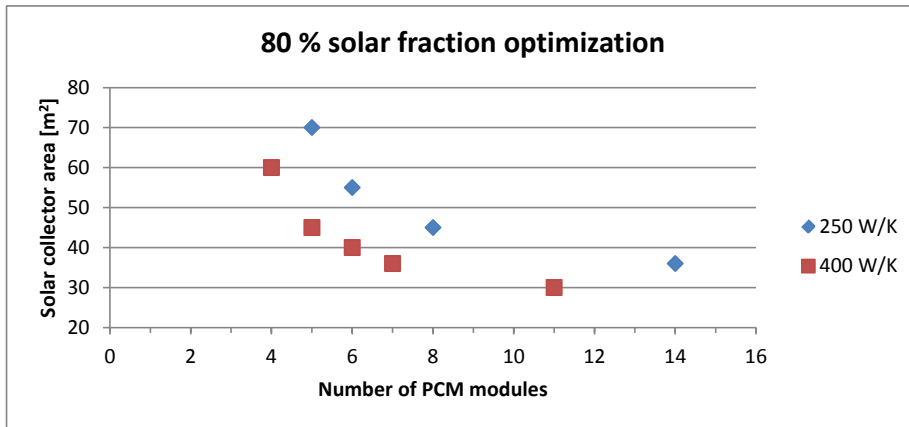
402 The results shown in Figure 6Figure 4 are for systems reaching 80% solar fraction. Values of 250 W/K and  
 403 400 W/K for the heat exchange capacity rate were selected. The solar collector area and the number of

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404 modules were varied. Based on the cost of the PCM modules and of the solar collectors [an](#) evaluation can  
405 be made to choose the optimum system [design and](#) size.



406  
407 **Figure 6. 80% solar fraction for systems with heat exchange capacity rate for the PCM storage of 250 W/K and 400 W/K.**

408 [Installation of such PCM storage systems in already built houses also leads to considerations related](#)  
409 [practically installation possibilities of access and handling. This could lead to restrictions of module size.](#)

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## 410 5. Conclusions

411 To have a reliable long term heat storage based on stable supercooling of sodium acetate trihydrate a  
412 number of problems have to be solved. Capacity loss due to phase separation can be solved by using  
413 thickening agents such as carboxyl methyl cellulose (CMC) and Xanthan rubber. The density difference of  
414 the sodium acetate trihydrate from the coldest to the hottest state is associated with pressure changes in a  
415 storage module. To obtain stable supercooling in large bulks of sodium acetate trihydrate in closed rigid  
416 tanks it is essential to operate the PCM chamber with minimal pressure changes. This can e.g. be done by  
417 having an expansion volume in the PCM chamber connected to an external expansion vessel without pre-  
418 pressure. The heat exchange capacity rate to and from the PCM can be improved by adding a highly  
419 conductive compound such as graphite powder to the PCM combined with a temperature stable thickening  
420 agent. The thickening agent has to be stable in the entire temperature interval the storage operates ~~at~~.  
421 Xanthan rubber has shown to keep its thickening ability up to 90°C. Cavities in the PCM are formed when  
422 the PCM contracts during crystallization. A heat transfer fluid inside the PCM chamber that does not react  
423 with the PCM can fill in these gaps and increase the heat exchange capacity rate. Triggering the  
424 crystallization of the supercooled sodium acetate can be done by providing a seed crystal or by cooling a  
425 small part of the PCM to its minimum level of supercooling e.g. by evaporating CO<sub>2</sub> [in a small chamber](#)  
426 [adjacent to the PCM chamber](#).

427 From theoretical consideration it is possible to store up to 230 kJ/kg of supercooled sodium acetate  
428 trihydrate at 20°C if all sensible heat down to 20°C can be utilized. A TRNSYS simulation showed that for a  
429 passive house in Danish climate it was possible to achieve a solar fraction of 80% by a solar heating system  
430 with 36 m<sup>2</sup> solar collector area and 7 PCM modules of 150 ~~liters~~ [L](#) if the heat exchange capacity rate was

431 400 W/K. If the heat exchange capacity rate was 250 W/K 12 modules were required to achieve 80% solar  
432 fraction. Based on this parametric study including system size and heat exchange capacity rate of the  
433 module it was obvious that a high heat exchange capacity rate is desired to reach a high solar fraction with  
434 smaller system sizes.

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### 442 **References**

- 443
- 444 [1] S.D. Sharma, K. Sagara, Latent Heat Storage Materials and Systems: A Review, *Int. J. Green Energy*. 2  
445 (2005) 1–56. doi:10.1081/GE-200051299.
- 446 [2] D.N. Nkwetta, F. Haghighat, Thermal energy storage with phase change material - A state-of-the art  
447 review, *Sustain. Cities Soc.* 10 (2014) 87–100. doi:10.1016/j.scs.2013.05.007.
- 448 [3] M.K.A. Sharif, a a Al-abidi, S. Mat, K. Sopian, M.H. Ruslan, Review of the application of phase change  
449 material for heating and domestic hot water systems, *Renew. Sustain. Energy Rev.* 42 (2015) 557–  
450 568. doi:10.1016/j.rser.2014.09.034.
- 451 [4] C. Solé, M. Medrano, A. Castell, M. Nogue, H. Mehling, L.F. Cabeza, Energetic and exergetic analysis  
452 of a domestic water tank with phase change material, *Int. J. ENergy Res.* 32 (2008) 204–214.  
453 doi:10.1002/er.
- 454 [5] T. Wada, F. Kimura, R. Yamamoto, Studies on salt hydrates for latent heat storage. II. Eutectic  
455 mixture of pseudo-binary system., *Bull. Chem. Soc. Jpn.* (1983) 1223–1226.
- 456 [6] S. Canbazoglu, A. Şahinaslan, A. Ekmekyapar, Ý.G. Aksoy, F. Akarsu, Enhancement of solar thermal  
457 energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-  
458 heating system, *Energy Build.* 37 (2005) 235–242. doi:10.1016/j.enbuild.2004.06.016.
- 459 [7] K. Nagano, K. Ogawa, T. Mochida, K. Hayashi, H. Ogoshi, Performance of heat charge/discharge of  
460 magnesium nitrate hexahydrate and magnesium chloride hexahydrate mixture to a single vertical  
461 tube for a latent heat storage system, *Appl. Therm. Eng.* 24 (2004) 209–220.  
462 doi:10.1016/j.applthermaleng.2003.09.002.
- 463 [8] A. López-navarro, J. Biosca-taronger, J.M. Corberán, C. Peñalosa, A. Lázaro, P. Dolado, et al.,  
464 Performance characterization of a PCM storage tank, *Appl. Energy*. 119 (2014) 151–162.  
465 doi:10.1016/j.apenergy.2013.12.041.

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- 466 [9] P. Arce, M. Medrano, A. Gil, E. Oró, L.F. Cabeza, Overview of thermal energy storage (TES) potential  
467 energy savings and climate change mitigation in Spain and Europe, *Appl. Energy*. 88 (2011) 2764–  
468 2774. doi:10.1016/j.apenergy.2011.01.067.
- 469 [10] A. Abhat, Short Term Thermal Energy Storage, *Energy Build.* 3 (1981) 49–76.
- 470 [11] J. Guion, M. Teisseire, Nucleation of sodium acetate trihydrate in thermal heat storage cycles, *Sol.*  
471 *Energy*. 46 (1991) 97–100.
- 472 [12] P. Hu, D.-J. Lu, X.-Y. Fan, X. Zhou, Z.-S. Chen, Phase change performance of sodium acetate  
473 trihydrate with AlN nanoparticles and CMC., *Sol. Energy Mater. Sol. Cells*. 95 (2011) 2645–2649.  
474 doi:10.1016/j.solmat.2011.05.025.
- 475 [13] H. Kimura, J. Kai, Phase change stability of sodium acetate trihydrate and its mixtures, *Sol. Energy*.  
476 35 (1985) 527–534. doi:10.1016/0038-092X(85)90121-5.
- 477 [14] G.A. Lane, *Solar heat storage latent heat material Vol 1*, Boca Raton, Florida, United states, 1983.
- 478 [15] J. Stanley, G.L. Hoerner, Reusable heat pack containing supercooled solution and means for  
479 activating same, (1978). [www.google.com/patents/US4077390](http://www.google.com/patents/US4077390) (accessed May 28, 2015).
- 480 [16] S. Hirano, T.S. Saitoh, Heat balance of long-term supercooled thermal energy storage, *Nihon Enerugi*  
481 *Gakkaishi/Journal Japan Inst. Energy*. 80 (2001) 1050–1059.
- 482 [17] S. Hirano, S. Takeo, INFLUENCE OF OPERATING TEMPERATURE ON EFFICIENCY OF SUPERCOOLED  
483 THERMAL ENERGY STORAGE, in: *IECEC 2002 Pap. No. 20040*, 2002: pp. 684–689.
- 484 [18] S. Hirano, T.S. Saitoh, Performance of Supercooled Thermal Energy Storage Unit with Practical  
485 Dimensions, *3rd Int. Energy Convers. Eng. Conf.* 2 (2005) 1293–1300.
- 486 [19] B. Sandnes, J. Rekstad, Supercooling salt hydrates: Stored enthalpy as a function of temperature,  
487 *Sol. Energy*. 80 (2006) 616–625. doi:10.1016/j.solener.2004.11.014.
- 488 [20] P.F. Barrett, B.R. Best, Thermal energy storage in supercooled salt mixtures, *Mater. Chem. Phys.* 12  
489 (1985) 529–536.
- 490 [21] B. Zalba, J.M. Marin, L.F. Cabeza, H. Mehling, Review on thermal energy storage with phase change:  
491 materials, heat transfer analysis and applications, *Appl. Therm. Eng.* 23 (2003) 251–283.
- 492 [22] S. Furbo, J. Fan, Heat Storage based on a NaCH<sub>3</sub>COO Water Mixture for Solar Heating Systems, DTU  
493 Civil Engineering, Report SR-12-10 (UK), Kgs. Lyngby, Denmark, 2012.
- 494 [23] M.A. Rogerson, S.S.S. Cardoso, Solidification in Heat Packs : I . Nucleation Rate, *AIChE J.* 49 (2003)  
495 505–515.
- 496 [24] L. Wei, K. Ohsasa, Supercooling and Solidification Behavior of Phase Change, *ISIJ Int.* 50 (2010) 1265–  
497 1269.



- 498 [25] T. Wada, F. Kimura, Y. Matsuo, Studies on salt hydrates for latent heat storage. IV. crystallization in  
499 the binary system, *Bull. Chem. Soc. Jpn.* 56 (1983) 3827–3829.
- 500 [26] H. Mehling, L.F. Cabeza, Materials used as PCM in thermal energy storage in buildings: A review,  
501 *Renew. Sustain. Energy Rev.* (2011) 1675–1695. doi:10.1016/j.rser.2010.11.018.
- 502 [27] S. Furbo, S. Svendsen, Report on heat storage in a solar heating system using salt hydrates, *Therm.*  
503 *Insul. Laboratory, DTU, Kgs. Lyngby, Denmark, Rep. 70.* (1977).
- 504 [28] S. Furbo, Investigations of Heat Storages with salt hydrate as storage medium based on the extra  
505 water principle, *Therm. Insul. Laboratory, DTU, Kgs. Lyngby, Denmark, Rep. 80. Meddelelse* (1978).
- 506 [29] N. Araki, M. Futamura, A. Makino, H. Shibata, Measurements of Thermophysical Properties of  
507 Sodium Acetate Hydrate, *International J. Thermophys.* 16 (1995) 1455–1466.
- 508 [30] L. Desgrosseilliers, P. Allred, D. Groulx, M.A. White, Determination of enthalpy-temperature-  
509 composition relations in incongruent-melting phase change materials, *Appl. Therm. Eng.* 61 (2013)  
510 193–197. doi:10.1016/j.applthermaleng.2013.07.019.
- 511 [31] L.F. Cabeza, G. Svensson, S. Hiebler, H. Mehling, Thermal performance of sodium acetate trihydrate  
512 thickened with different materials as phase change energy storage material, *Appl. Therm. Eng.* 23  
513 (2003) 1697–1704. doi:10.1016/S1359-4311(03)00107-8.
- 514 [32] T. Wada, R. Yamamoto, Y. Matsuo, Heat storage capacity of sodium acetate trihydrate during  
515 thermal cycling, *Sol. Energy.* 33 (1984) 373–375. doi:10.1016/0038-092X(84)90169-5.
- 516 [33] H.W. Ryu, S.W. Woo, B.C. Shin, S.D. Kim, Prevention of supercooling and stabilization of inorganic  
517 salt hydrates as latent heat storage materials, *Sol. Energy Mater. Sol. Cells.* 27 (1992) 161–172.  
518 doi:10.1016/0927-0248(92)90117-8.
- 519 [34] B.M.L. Garay Ramirez, C. Glorieux, E.S. Martin Martinez, J.J. a Flores Cuautle, Tuning of thermal  
520 properties of sodium acetate trihydrate by blending with polymer and silver nanoparticles, *Appl.*  
521 *Therm. Eng.* 61 (2013) 838–844. doi:10.1016/j.applthermaleng.2013.09.049.
- 522 [35] G. Lane, *Solar heat storage latent heat material Vol 2*, CRC, Boca Raton, Florida, United states, 1986.
- 523 [36] T. Wada, Studies on sodium acetate trihydrate for latent heat storage, Osaka University, Japan,  
524 1985. hdl.handle.net/11094/2830.
- 525 [37] X. Jin, S. Zhang, M. a. Medina, X. Zhang, Experimental study of the cooling process of partially-  
526 melted sodium acetate trihydrate, *Energy Build.* 76 (2014) 654–660.  
527 doi:10.1016/j.enbuild.2014.02.059.
- 528 [38] M.A. Rogerson, S.S.S. Cardoso, Solidification in heat packs: I. Nucleation rate, *AIChE J.* 49 (2003)  
529 505–515. doi:10.1002/aic.690490220.
- 530 [39] L.F. Cabeza, J. Roca, M. Nogués, H. Mehling, S. Hiebler, Immersion corrosion tests on metal-salt  
531 hydrate pairs used for latent heat storage in the 48 to 58 8C temperature range, *Mater. Corros.* 53  
532 (2002) 902–907.

- 533 [40] M.A. Rogerson, S.S.S. Cardoso, Solidification in Heat Packs : III . Metallic Trigger, *AIChE J.* 49 (2003)  
534 522–529.
- 535 [41] A.E.M. Anthony, P.F. Barrett, B.K. Dunning, Verification of mechanism for nucleating crystallization  
536 of supercooled liquids, *Mater. Corros.* 25 (1990) 199–205.
- 537 [42] P.F. Barrett, D.K. Benson, A mechanism for nucleating supercooled liquids, *Mater. Chem. Phys.* 20  
538 (1988) 171–178.
- 539 [43] W.-B. Ye, D.-S. Zhu, N. Wang, Fluid flow and heat transfer in a latent thermal energy unit with  
540 different phase change material (PCM) cavity volume fractions, *Appl. Therm. Eng.* 42 (2012) 49–57.  
541 doi:10.1016/j.applthermaleng.2012.03.002.
- 542 [44] M. Medrano, M.O. Yilmaz, M. Nogués, I. Martorell, J. Roca, L.F. Cabeza, Experimental evaluation of  
543 commercial heat exchangers for use as PCM thermal storage systems, *Appl. Energy.* 86 (2009) 2047–  
544 2055. doi:10.1016/j.apenergy.2009.01.014.
- 545 [45] A. Heinz, Application of Thermal Energy Storage with Phase Change Materials in Heating Systems,  
546 Graz University of Technology, Austria, 2007.
- 547 [46] W. Li, J. Mao, L. Wang, L. Sui, Effect of the Additive on Thermal Conductivity of the Phase Change  
548 Material, *Adv. Mater. Res.* 399-401 (2011) 1302–1306. doi:10.4028/www.scientific.net/AMR.399-  
549 401.1302.
- 550 [47] F. Frusteri, V. Leonardi, G. Maggio, Numerical approach to describe the phase change of an inorganic  
551 PCM containing carbon fibres, *Appl. Therm. Eng.* 26 (2006) 1883–1892.  
552 doi:10.1016/j.applthermaleng.2006.01.018.
- 553 [48] H.K. Shin, M. Park, H.-Y. Kim, S.-J. Park, Thermal property and latent heat energy storage behavior of  
554 sodium acetate trihydrate composites containing expanded graphite and carboxymethyl cellulose  
555 for phase change materials, *Appl. Therm. Eng.* 75 (2015) 978–983.  
556 doi:10.1016/j.applthermaleng.2014.10.035.
- 557 [49] L.F. Cabeza, H. Mehling, S. Hiebler, F. Ziegler, Heat transfer enhancement in water when used as  
558 PCM in thermal energy storage, *Appl. Therm. Eng.* 22 (2002) 1141–1151. doi:10.1016/S1359-  
559 4311(02)00035-2.
- 560 [50] D.N. Nkwetta, P.-E. Vouillamoz, F. Haghighat, M. El-Mankibi, A. Moreau, A. Daoud, Impact of phase  
561 change materials types and positioning on hot water tank thermal performance: Using measured  
562 water demand profile, *Appl. Therm. Eng.* 67 (2014) 460–468.  
563 doi:10.1016/j.applthermaleng.2014.03.051.
- 564 [51] K. Seo, S. Suzuki, T. Kinoshita, I. Hirasawa, Effect of Ultrasonic Irradiation on the Crystallization of  
565 Sodium Acetate Trihydrate Utilized as Heat Storage Material, *Chem. Eng. Technol.* 35 (2012) 1013–  
566 1016. doi:10.1002/ceat.201100680.
- 567 [52] W. Streicher, J. Bony, S. Citherlet, A. Heinz, P. Pusching, H. Schranzhofer, et al., Simulation Models of  
568 PCM Storage Units, IEA Solar Heating and Cooling programme - Task 32 “Advanced storage concepts

- 569 for solar and low energy, Report C5 of Subtask C buildings,” Institute of Thermal Engineering Graz  
570 University of Technology, Austria, 2008.
- 571 [53] J.M. Schultz, S. Furbo, Investigation of heat of fusion storage for solar low energy buildings, Proc.  
572 Sol. World Congr. 2005 Bringing Water To World, Incl. Proc. 34th Ases Annu. Conf. Proc. 30th Natl.  
573 Passiv. Sol. Conf. Proc. Sol. World Congr. Bringing Water World, Incl. Proc. Ases Annu. 3 (2005)  
574 1833–1838.
- 575 [54] Statens Byggeforskningsinstitut, tsbi3, (1993). [www.sbi.dk](http://www.sbi.dk).
- 576 [55] Passive House Institute, Passive House Institute, (n.d.). [www.passiv.de/en/index.php](http://www.passiv.de/en/index.php) (accessed May  
577 28, 2015).
- 578 [56] J. Schultz, S. Furbo, Solar heating systems with heat of fusion storage with 100% solar fraction for  
579 solar low energy buildings, in: ISES Sol. World Congr. 2007 Proc., 2007: pp. 2721–2725.

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