



Design and functionality of a segmented heat-storage prototype utilizing stable supercooling of sodium acetate trihydrate in a solar heating system



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HIGHLIGHTS

- Combined short- and long-term heat-storage prototype for domestic solar heating.
- Interplay of solar collectors, four 200 kg PCM units and a 735 L water tank.
- Functionality of a segmented heat storage utilizing stable supercooling of SAT.
- Solidification of supercooled SAT was started by a seed crystal injection device.
- Supply temperatures and thermal power during PCM charge and discharge were evaluated.

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ABSTRACT

A solar heating system with 22.4 m² of solar collectors, a heat storage prototype consisting of four 200 kg phase-change material (PCM) storage units, and a 735 L water tank was designed to improve solar heat supply in single-family houses. The PCM storage utilized stable supercooling of sodium acetate trihydrate composites to conserve the latent heat of fusion for long-term heat storage. A control strategy directed heat from a solar collector array to either the PCM storage or a water buffer storage. Several PCM units had to be charged in parallel when the solar collector output peaked at 16 kW. A single unit was charged with 27.4 kWh of heat within four hours on a sunny day, and the PCM temperature increased from 20 °C to 80 °C. The sensible heat from a single PCM unit was transferred to the water tank starting with about 32 kW of thermal power after it had fully melted at 80 °C. A mechanical seed crystal injection device was used to initialize the crystallisation of the sodium acetate trihydrate after it had supercooled to room temperature. The unit discharge during solidification peaked at 8 kW. Reliable supercooling was achieved in three of the four units. About 80% of latent heat of fusion was transferred from PCM units after solidification of supercooled sodium acetate trihydrate to the water tank within 5 h. Functionality tests with practical operation conditions on the novel, modular heat-storage configuration showed its applicability for domestic hot water supply and space heating.

1. Introduction

With the increasing utilization of energy from renewable sources, solar heating has become one of the most promising technologies for reducing the percentage of fossil fuels in future energy systems. Thermal energy storage is a key system component for utilizing renewable energy sources to a greater extent [1]. Solar combisystems are designed to achieve high solar fractions of heat supply for domestic buildings. Their task is to collect energy from the sun and store it until it is used for domestic hot water or for space heating/cooling. The importance of heat storage with small heat loss and good interplay with solar collectors is well known [2,3]. Andersen and Furbo [4] and Thür

and Furbo [5] have conducted detailed investigations on the design and potential of solar combisystems and on efficient heat storage using hot water storage tanks.

Due to insufficient solar radiation during the winter and the high energy requirement for space heating at high latitudes, long-period and even seasonal heat storage technology for solar heating applications has attracted more and more attention in recent decades [6,7].

1.1. Novel thermal energy storage concepts

Materials that might enable more efficient storage of heat over long periods, were investigated by Ristić et al. [8]. Promising heat storage

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Nomenclature*Dimensional variables*

c_p	specific heat capacity (kJ/kg K)
G	global irradiance (W/m ²)
m	mass (kg)
Q	thermal energy, heat (kWh)
\dot{Q}	thermal power, heat transfer rate (kW)
ρ	density (kg/m ³)
t	time (s)
T	temperature (°C)
\dot{V}	volume flow rate (l/min)

Greek letters

Δh	specific latent heat of fusion (kJ/kg)
ΔH	latent heat of fusion (kJ)
ΔT	temperature difference (K)

Subscripts

AMB	ambient
B	buffer heat storage (water tank)
COLL	solar collector
IN	inlet line

L	lower
LOSS	losses
PCM	phase-change material
OUT	outlet line
S	surface
ST	steel
TOTAL	total, on the collector plane
U	upper
W	water

Abbreviations

ABS	acrylonitrile butadiene styrene
CMC	carboxymethyl cellulose
DHW	domestic hot water
EDTA	ethylenediaminetetraacetic acid
HTF	heat transfer fluid
HX	heat exchanger
P	pump
PCM	phase-change material
SA	sodium acetate
SAT	sodium acetate trihydrate
SH	space heating
V	2-way valve

concepts are based on solid sorption materials which utilize the adsorption of water vapour [9–11], the principle of absorption (e.g. with sodium-hydroxide and water [12] as demonstrated by Fumey et al. [13] and Dagueuet-Frick et al. [14]), thermochemical reactions (as demonstrated by Zondag et al. [15]), and phase-change materials (PCMs). Salt hydrate reactions have been considered for their high potential energy storage density [16]. The thermophysical properties of several salt hydrates are appropriate for utilization as PCMs in building applications [17].

As reported by Quinell and Davidson [18], the combined use of material properties, such as reaction enthalpy and sensible heat capacity, is potentially advantageous in new materials for domestic heat storage applications. The stable supercooling of PCMs allows the combined use of the latent heat of fusion and sensible heat capacity. This is one long-term heat storage concept that promises more efficient utilization of solar heat for low-energy buildings in summer and transitional seasons [19]. In addition to salt hydrates, microstructured polyol–polystyrene composites have also been considered for their stable supercooling properties [20].

Sodium Acetate Trihydrate (SAT) is a salt hydrate with a melting point of 58 °C and a relatively high latent heat of fusion (264 kJ/kg) [21]. It contains 60.3%wt of sodium acetate and 39.7%wt of water. If SAT has been fully melted and heated to a temperature higher than ~77 °C (as indicated in the binary phase diagram of sodium acetate and water [22]), it can cool down to ambient temperature in its liquid phase without releasing the heat of fusion; this is called “supercooling”, “subcooling” or “undercooling”. The latent heat is conserved until crystallization occurs. When a PCM is in the supercooled state and in thermal equilibrium with its surroundings, it can in principle store heat indefinitely, so it could be used for seasonal heat storage [23]. Once crystallization is activated, the latent heat of fusion is released, and the material temperature increases almost immediately to the melting temperature [24].

On the other hand, the cooling down of liquid material to temperatures substantially below its melting temperature is considered to hinder the conventional use of PCMs for thermal energy storage [25,26]. Ways of reducing the supercooling of SAT have therefore been investigated [27,28].

Various designs have been developed for domestic heat storage units using PCMs. The performance of heat exchangers with large PCM volumes in metal containers with an internal bundle of tubes has been studied by Lopez-Navarro et al. [29]. Shell-and-tube heat exchangers [30] and macro encapsulated PCM in water vessels [31] have been tested for sensible-latent heat storage. Moreno et al. [32] have investigated the corrosion of metal and metal alloy containers in contact with various PCMs. Arteconi et al. [33] argue that the application of PCMs in thermal energy storage systems can help manage the mismatch between the availability of renewable electricity and the demand for electricity, for example in buildings where hot water, heating and cooling are delivered by heat pumps and air conditioning.

1.2. Sodium acetate trihydrate compositions

SAT is available in large quantities in food-grade products (E262i), which makes it suitable for application in domestic buildings. To stabilize SAT for heat storage applications, adding water (resulting in a lower SA-water ratio) was first studied by Furbo in 1978 [34]. Later investigations on a heat storage unit containing about 200 kg of an SA-water composition with a water content greater than 40%wt [35] showed a decrease in conserved latent heat of fusion when several cycles of heating and cooling were applied.

To overcome the problem of phase separation in the incongruently melting SAT, various additives can be added to form a more stable composition. One proposed solution is to add Carboxymethyl Cellulose (CMC) as a thickening agent [36]. The main drawback of thickening agents is that they reduce heat transfer by convection. Highly conductive graphite powder can improve the thermal conductivity of a composition with a thickening agent [37]. Paraffin oil, which does not mix with SAT, can be added to increase heat transfer by filling insulating cavities formed during the solidification and contraction of the PCM composition [38] due to density differences during phase change [37]. Another way of reducing the problem of phase separation is to increase the solubility of the crystal water in the melted and supercooled SAT mixture. The heat contents of SAT composites with various concentrations of thickening agents, the chelating agent Disodium

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