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## Research Paper

## Thermal performance of sodium acetate trihydrate based composite phase change material for thermal energy storage



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## HIGHLIGHTS

- The compatibility of sodium acetate trihydrate was tested.
- The sodium acetate trihydrate was modified with five kinds of nucleating agents to reduce the supercooling.
- The heat storage units based on the copper foam/ modified sodium acetate trihydrate were proposed.
- The heat charging and discharging performance of heat storage unit was investigated.

## ARTICLE INFO

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## ABSTRACT

Sodium acetate trihydrate (SAT) as a phase change material (PCM) suffers from large supercooling, unclear compatibilities and low thermal conductivity. In this paper, the compatibility of SAT was tested for 270 days with aluminum alloy and copper. The corrosion phenomenon was evaluated by the scanning electron microscope (SEM) images and EDS (energy dispersive spectrum) analyses, which indicated that the corrosion effect could be neglected. Then, SAT modified with the additives of 2 wt% disodium hydrogen phosphate dodecahydrate (DHPD) and 2 wt% carboxyl methyl cellulose (CMC) showed the best performance in reducing supercooling. Finally, a laboratory-scale experiment was conducted to investigate the heat-charging and discharging performance of the heat storage units based on a copper foam/SAT composite PCM. The findings indicated that the heat-charging rate was based mainly on the heat power level, and the composite PCM with fewer thermal conductivity enhancers showed better heat storage performance. The heat discharging process revealed that the heat storage units still had more supercooling than the modified SAT. Based on the results obtained, the copper foam/SAT composite PCM appears to be a promising heat storage material, while the supercooling still needs to be considered in application.

## 1. Introduction

With the progressive intensification of energy shortages and environmental pollution [1–3], it becomes more urgent to improve energy efficiency, energy saving and emission reduction. Thermal energy storage is an important component of an energy application system, which could ease the mismatch in time and location between energy demands and supply [1,4–7]. In general, thermal energy storage can be divided into three groups: sensible energy storage, chemical energy storage and latent thermal energy storage. Compared with sensible energy storage and chemical energy storage, latent thermal energy storage is a more effective energy storage method because of the high storage energy density, suitable phase change temperature, stable chemical properties and low cost, and latent thermal energy storage has been widely used in

the field of solar energy storage [8], building energy management systems [9,10], waste heat recovery systems [11,12] and thermal management systems [13,14]. The several kinds of phase change materials (PCMs) could be divided into three groups: the organic PCMs, the inorganic PCMs and the eutectic PCMs [15,16]. Many organic PCMs such as paraffin, sugar alcohols and fatty acids always have the drawbacks of relatively high cost, low thermal energy storage density and flammability, which are non-negligible and constrain the practical application of organic PCMs. Comparatively, the inorganic PCMs, especially hydrated salts, whose melting point ranges from a few degrees Celsius to over 100 °C always possess superior properties such as higher thermal energy storage density, better thermal conductivity, non-flammability and lower cost, which indicate that hydrated salts can be widely applied under the working conditions of human activities,

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domestic instruments and equipment.

Sodium acetate trihydrate ( $\text{CH}_3\text{COONa}\cdot 3\text{H}_2\text{O}$ , SAT) with the melting point of  $\sim 58^\circ\text{C}$  is a representative of hydrate salt PCMs, which could easily be integrated with space heating and domestic hot water preparation [17], solar heating systems [18], and radiant floor heating systems [19]. However, SAT always suffers from serious supercooling problems and low thermal conductivity during the thermal energy storage process as most hydrated salts are [20]. Aiming at overcoming the drawbacks of SAT, extensive efforts have been conducted. Jin et al. [21] performed an experiment involving the cooling processes of a partially melted SAT. The results showed that the degree of supercooling of partially melted SAT increased with the elevation of the heating temperature. Zhou and Xiang [22] experimentally investigated the stable supercooling characteristics of an SAT mixture within three types of thermal storage units, indicating that the inner surface roughness, cooling rate, salt-water mass ratio and carboxyl methyl cellulose could all affect the stable supercooling of the SAT. Several kinds of nucleating agents and thickeners were selected by Mao et al. [23] to improve the phase-change energy storage properties of SAT. The experimental results indicated that adding disodium hydrogen phosphate dodecahydrate can reduce the degree of supercooling. Cabeza et al. [24] conducted an experiment to find the effective thickeners for SAT and discovered that SAT could be thickened successfully with starch and bentonite, with the mixtures showing a melting point similar to the SAT, and the enthalpy would decrease with the type and the amount of changing of the thickeners. Fashandi and Leung [25] found that adding a bio-derived chitin nanowhisker was an effective way to suppress the supercooling of SAT. Different mass fractions of silver nanoparticles were experimentally studied by Ramirez et al. [26] to reduce the supercooling of SAT.

The heat transfer enhancement is another key issue for the SAT applied as a PCM for thermal energy storage. Some thermal conductivity enhancers such as nanoparticles, metal foams and graphite materials can not only reduce the degree of supercooling but could also effectively improve the thermal conductivity of SAT. Cui et al. [27] reported that adding Nano-Cu could not only reduce the degree of supercooling of SAT but also increase the thermal conductivity of the composite SAT by nearly 20% compared to the pure SAT. Johansen et al. [28] investigated the effects on the thermal conductivity and supercooling stability of SAT of adding graphite powder. The results showed that the graphite powder was a promising thermal conductivity enhancer. A series of expanded graphite-based composite PCMs using an SAT-urea non-eutectic mixture was prepared and tested by Fu et al. [19]. The test results showed that the composite PCMs with the mass fraction of 8% had the thermal conductivity of 2.076 W/mK and the degree of supercooling of  $1.54^\circ\text{C}$ . Mao et al. [29] prepared a novel composite phase-change material based on SAT by adding a certain proportion of expanded graphite, which showed a relatively small degree of supercooling and larger thermal conductivity. They [30] also proposed a series of SAT-disodium hydrogen phosphate dodecahydrate-carboxyl methyl cellulose/expanded graphite composite PCMs. They concluded that the composite PCM with 3 wt% expanded graphite had the most suitable thermal properties and that the degree of supercooling and the thermal conductivity were  $2^\circ\text{C}$  and 1.37 W/mK, respectively. Shin et al. [31] proposed a series of SAT composites containing different mass fractions of expanded graphite and carboxymethyl cellulose. The measured results manifested that expanded graphite could effectively improve the thermal conductivity and diminish the supercooling effect of SAT. Dannemand et al. [32] prepared a series of SAT-based composite PCMs and measured their thermal conductivity. The results revealed that the composite PCM with SAT, 1% xanthan rubber and 5% graphite flakes had the highest thermal conductivity of 1.1 W/m K. Li et al. [33] studied the supercooling and thermal conductivity of the SAT composited with copper foam, which showed smaller degree of supercooling and larger thermal conductivity than the pure SAT.

For the hydrated salts, the compatibility of the thermal conductivity additives and the encapsulation materials with the PCM is a key issue to ensure the long-term applications of PCM-based thermal energy storage systems. The corrosion resistance of commercial metals in contact with several hydrated salts with the melting point ranging from  $32$  to  $58^\circ\text{C}$  was tested by Cabeza et al. [34,35] with a duration up to 70 days. They found that the SAT had a slight corrosion effect on the copper and had almost no effect on the aluminum. Moreno et al. [36] experimentally evaluated the corrosion rate of two metals and two metal alloys that were in contact with different hydrated salt PCMs by weighing the mass change. Five kinds of container materials were immersed by Browne et al. in five different PCMs for a period of 722 days to investigate the compatibility of PCM with various materials [37]. The results showed that the steel was the most suitable container materials for all the PCMs.

Considering the above-mentioned papers, various methods have been proposed for reducing the degree of supercooling, diminishing the phase separation, improving thermal conductivity and investigating the compatibility of SAT. The thermal conductivity of the solid SAT ranged from 0.17 W/mK to 0.7 W/mK [27,32,38] at different temperatures, and the thermal properties of the SAT composite varied significantly with different additives at different mass fraction [20,32,39]. Most related papers either reported the thermal properties of the composite SAT or focused on the thermal energy storage performance. Few research studies were systematically related to the modification of the SAT and its thermal energy storage performance. The compatibility of SAT with metals was tested with the immersion corrosion method and evaluated by weighing the mass changes. Little information about the analysis of the microphenomenon of corrosion was reported in detail. Consequently, it is valuable to systematically investigate the thermal property modification of the SAT and the thermal energy storage performance of the composite SAT-based PCM, and the compatibility of the SAT with commonly used metals. In the present study, the compatibility of SAT was investigated first. Second, the SAT was composited with different additives (disodium hydrogen phosphate dodecahydrate (DHPD), sodium carbonate decahydrate (SCD), sodium silicate nonahydrate (SCN), borax decahydrate (BDH), and quart sand (QS)) to modify the supercooling, and the carboxymethyl cellulose (CMC) was used as a thickening agent. Finally, two kinds of copper foam/hydrated salt composite PCMs were prepared by using the copper foams as supporting matrixes and the modified SAT as PCM, and the thermal energy storage performance of the composite PCMs was evaluated by funding a small-scale experimental test unit.

## 2. Materials and instruments

SAT, DHPD, SCD, SCN, BHD, QS and CMC (analytical reagent grade, purity > 99%) were purchased from Sinopharm Chemical Reagent Co., Ltd. (Beijing, China). Copper foams with the pore size of 20 PPI (PPI means the numbers of pores in per inch) and the porosity of 0.98 and 0.88 were offered by Zhuoer Technology Co. Ltd. (Changchun, China).

The apparatus used for the experiments included a differential scanning calorimeter (DSC, 214 Polyma, Netzsch, Germany), an energy dispersive spectroscope (EDS, Hitachi Inc., Japan), scanning electron microscope (SEM, Hitachi S4800, Hitachi Inc., Japan), several PT100 temperature sensors (precision  $\pm 0.1^\circ\text{C}$ ), DC power supply module by Beisina Technologies (SNK-22H06, 0-220 V/0-6 A), data acquisition module (ADVANTECH ADAM-4015), and a high-low temperature test chamber (BPH-120B, Shanghai Everone Precision Instruments Co., Ltd., China).

## 3. Experimental work

### 3.1. Preparation of SAT composites

SAT was selected as the phase change material for thermal energy storage. However, the pure SAT has a considerably large degree of

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