

# Comparative Study on the Thermodynamic Performance of the Solar Latent Heat Thermal Energy Storage System Using Different Storage Mediums<sup>#</sup>

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## ABSTRACT

In this study, a low-carbon solar water heating system integrated with salt hydrates as storage mediums was developed. The thermal performance of the heating system was tested using a full-scale experimental platform. A performance comparison was conducted between the system using sodium acetate trihydrate (SAT)-acetamide (AC) and one using SAT. The heating system incorporating the SAT-AC (phase-change temperature: 47.8 °C) showed an approximate 5.3% increase in the coefficient of performance compared to the system using SAT (phase-change temperature: 56 °C). Additionally, the discharging time for the SAT-AC unit was extended, benefiting from its optimal phase-change temperature. These findings indicate the promising potential of the selected salt hydrates for solar water heating applications and provide valuable guidelines for designing efficient heating systems.

**Keywords:** solar heat collector, salt hydrates, latent heat thermal energy storage, phase-change temperature, energy efficiency

## 1. INTRODUCTION

Due to the high consumption of non-renewable energy in heating applications for building sectors, novel approaches incorporating integrated renewable energy sources for highly efficient hot water production have become essential. Compared with other alternative sources, solar energy is much less constrained to geographical conditions and application environments. Considering the instability of renewable energy sources and the stochastic hot water demand profiles, the latent heat thermal energy storage (LHTES) technique has been introduced due to the high storage density and constant phase-change temperature of phase-change material (PCM) [1].

Recently, the LHTES technique using phase-change material (PCM) as the storage medium has garnered

significant attention. Lin et al. designed a novel spiral-tube LHTES unit encapsulating sodium acetate trihydrate (SAT) as the storage medium [2]. The performance of the heat exchanger during charging and discharging was evaluated based on drain water temperature, heat exchange power, and accumulated energy under constant inlet conditions. The storage unit has a compact structure and large thermal capacity. Additionally, the LHTES technique has proven beneficial to the overall performance of solar heating systems. Abuşka et al. experimentally examined the thermal performance of a solar air collector combine with a PCM-honeycomb core under natural convection conditions [3]. A 10°C advantage in the peak melting point was observed when using a honeycomb core to enhance heat transfer in the PCM. Al-Kayiem et al. evaluated and compared the performance of a solar water heater integrated with PCM and PCM nanocomposite [4]. The introduction of LHTES significantly enhanced the solar water heater performance; however, the impact of the nanocomposite on system efficiency was negligible.

To achieve an efficient heating system and provide a consistent heat supply for the end-user, the phase-change temperature of the storage medium needs to be fitted well with the operating temperature range of the heating device. Badiei et al. numerically examined the performance of a flat plate collector integrated with different melting temperature PCMs [5]. The average daily efficiency of the collector was enhanced by 13.3% by adding the PCM with minimum melting temperature. Ding et al. compared the power consumption of an auxiliary electric heater of a solar water heating system combined with different PCMs [6]. The power consumption of the electric heater decreased as the phase-change temperature was reduced within the investigated temperature range.

Melting temperature is one of the most important indicators in the design of PCMs. A few studies have dealt

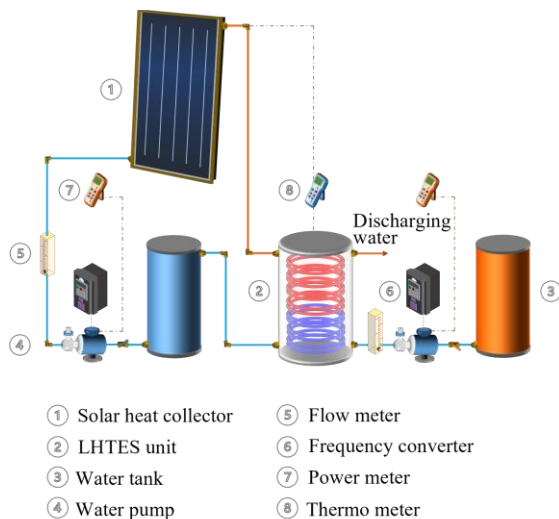
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with the impact of the melting process of the storage medium on the thermal performance of the solar water heating system through experimental methods. However, the implementation of the solar water heating system in combination with salt hydrates and the performance comparison between the system integrated with different storage mediums have seldom been experimentally conducted.

To achieve cost-effective and environmentally friendly hot water production, a low-carbon water heating system was designed in this study. The LHTES technique using salt hydrates as the storage medium was integrated into the solar water heating system. The sodium acetate trihydrate (SAT)-acetamide (AC) composite phase-change material (CPCM) and the SAT CPCM could be adopted as potential thermal energy storage mediums for the solar water heating system due to their appropriate phase-change temperatures [7]. An experimental test stand was built to examine the feasibility of the entire solar heating system for hot water supply. The dynamic thermal performance of the developed heating system under different PCM parameters was evaluated. The temperature evolution, energy efficiency, and discharging water temperature of the two configurations were compared to explore the impacts of the storage medium on the thermal performance of the solar LHTES system.

## 2. EXPERIMENTAL INVESTIGATION

### 2.1 System configuration



*Fig. 1 Schematic diagram of the test rig of the solar latent heat thermal energy storage*

An experimental test stand of the solar heating system integrated with different storage mediums was built in an air-conditioned laboratory to conduct a

comparison investigation. The schematic diagram of the setup is depicted in Fig. 1. The test stand includes solar simulators, a solar heat collector (SHC), an LHTES unit, water tanks, and water pumps. Tungsten-halogen lamps were assembled as artificial solar simulators to provide a controlled solar simulated condition for the comparison investigation [8]. The operation conditions of the heating system were kept the same for each scenario by testing in a controlled environment chamber with a temperature of  $21 \pm 2.0$  °C and a relative humidity ratio of  $70 \pm 5.0$  %. It was assumed that the test environment remained constant throughout the experiment. The effects of the phase-change behavior of the storage medium on the dynamic performance of the heating system were analyzed by comparing the temperature variation of the storage medium, energy efficiency, and discharging water temperature. Technical parameters of the main components used in the experimental test stand were detailed in our previous study [9].

### 2.2 Materials

SAT ( $\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$ ) produced by Tianjin Damao Chemical Reagent Factory was employed as the basic inorganic PCM [10,11]. AC ( $\text{CH}_3\text{CONH}_2$ ) produced by the same supplier was selected as the melting point modification agent for SAT. Disodium hydrogen phosphate dodecahydrate ( $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ ), also from the same supplier, was introduced as a nucleator to address the supercooling issue of salt hydrates. Carboxymethylcellulose ( $\text{R}_n\text{OCH}_2\text{COONa}$ ) purchased from Tianjin Zhiyuan Chemical Reagent Co., Ltd was added as a thickener to prevent phase separation.

The storage mediums were prepared using the melt-blending method. SAT mixtures with certain combinations were first melted and then mechanically agitated to ensure uniform dispersion. The phase-change temperature and enthalpy of the samples were characterized using differential scanning calorimetry (DSC) 214 Polyma (Netzsch-Gerätebau GmbH Co., Ltd, Germany). Samples were tested within the temperature range of 0 °C to 80 °C at a heating rate of 5 °C/min. Thermal conductivity of the samples was measured using the TPS 2200 Hot Disk Thermal Constants Analyzer (Hot Disk Inc., Sweden). The supercooling degree of the samples was tested based on the “T-history” method, known for its high accuracy in characterizing the crystallization performance of salt hydrates. The DSC curves of the selected storage mediums are shown in Fig. 2. Compared with SAT CPCM, the melting point of SAT-AC CPCM was reduced to 47.8 °C due to the addition of the melting point modification agent. Other

thermophysical properties of the two storage mediums are compared in Table 1.

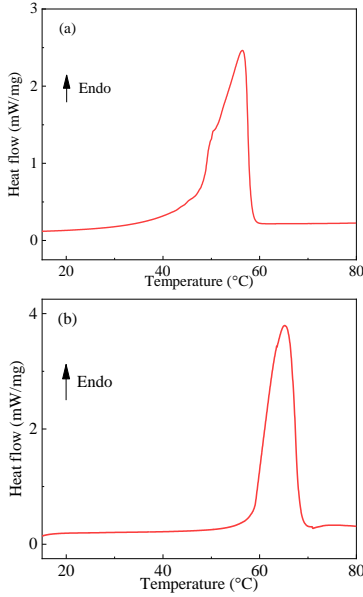


Fig. 2 DSC curves of (a) SAT-AC and (b) SAT CPCMs

Table 1 Thermophysical properties of the selected storage mediums

Item	SAT-AC	SAT
Melting point (°C)	47.8	58.2
Latent heat (kJ/kg)	217.5	265.1
Supercooling degree (K)	<5.0	<5.0
Thermal conductivity (W/(m·K))	0.290	0.380

### 2.3 Experimental scenarios

To determine the accuracy of the indoor tests, the thermal performance of a solar water heating system operated in both outdoor and indoor environments was compared first. The system design remained consistent across all tests, as shown in Fig. 3. In the outdoor test, the solar water heating system was activated during peak solar periods at noon for five hours. Specific parameters, including solar radiation intensity and ambient environment temperature, were recorded and depicted in Fig. 4. The test conditions for the indoor test were set to the average values observed during the outdoor test. The SHC was exposed to tungsten halogen lamps to collect heat during the indoor test. Temperature variations in the water tank was monitored via thermocouples and recorded via a temperature recorder in both tests. Further indoor tests were conducted to compare the thermal performance of the heating system when combined with different salt hydrates. The HTF went through the SHC and storage units in sequence to gradually heat the LHTES medium. The charging process lasted for eight hours, after which

the solar simulators were turned off, and the main water was pumped into the storage unit to extract stored heat during the discharging process. The exiting and incoming temperature of the SHC and the temperature distribution of the storage unit were monitored and recorded during the test. Power variations of each device were detected using a power quality analyzer. To analyze the effect of phase-change behavior on the thermodynamic performance of the solar heating system, the system integrated with different storage mediums was tested under a same irradiance of 850 W/m<sup>2</sup> and a flow rate of 30 g/s.

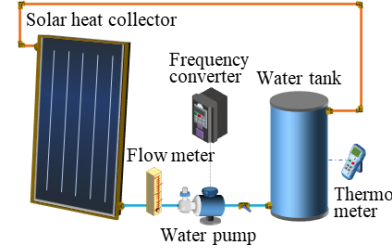


Fig. 3 Schematic diagram of the test rig of the solar water heating system.

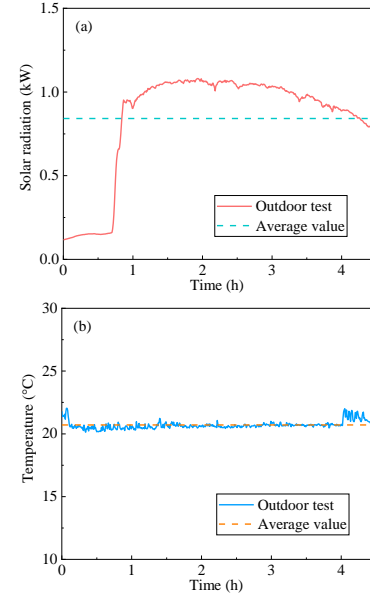


Fig. 4 (a) Solar radiation intensity and (b) ambient temperature of the outdoor and indoor tests.

### 2.4 Data processing

The thermal performance of the SHC was evaluated using the energy efficiency ( $\eta_{SHC}$ ).

$$\eta_{SHC} = \frac{Q_{SHC}}{Q_{solar}} = \frac{\dot{m}_{HTF} c_{p,HTF} (T_{SHC,out} - T_{SHC,in})}{AI} \quad (1)$$

The instantaneous coefficient of performance (COP) of the heating system was determined by the following equation:

$$COP_{sys} = \frac{Q_{SHC}}{W_{pump}} = \frac{\dot{m}_{HTF} c_{p,HTF} (T_{SHC,out} - T_{SHC,in})}{W_{pump}} \quad (2)$$

where  $W_{pump}$  is the power applied to the water pump.

### 3. RESULTS AND DISCUSSIONS

The temperature variations of the water tank in indoor and outdoor tests were compared to characterize deviations between the two conditions. As seen in Fig. 5, both temperature curves exhibit an increasing trend during the charging process. The variability of the real solar irradiation leads to a non-uniform temperature growth in the outdoor test. Initially, weaker solar irradiation slowed the temperature rise, but as solar radiation intensity increased, the temperature rise rate also increased, eventually decreasing again with lower solar radiation. The temperature of the water tank in the indoor test increased almost linearly due to the relatively stable solar source. A slight difference was discovered between the indoor and outdoor measurements, attributed to the mismatch between the spectral irradiance of the simulator and real solar irradiance. However, the temperature rise in both tests was similar, with an average difference of 6.3%, suggesting that the solar simulator could provide reliable irradiance for further comparative tests. Subsequent comparisons focused on the thermal dynamic performance of the heating system using SAT-AC CPCM and SAT CPCM as storage mediums.

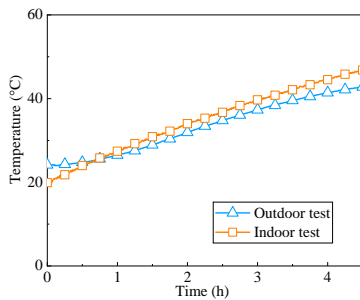


Fig. 5 Temperature comparison of the water tank in the outdoor and indoor tests.

The temperature variations of the selected LHTES mediums during the charging process are given in Fig. 6. Both storage mediums exhibited an initial rapid temperature rise during the first sensible heating phase, followed by a slower rise during the second latent heating phase. This slower increase is caused by the large phase-change enthalpy of the storage medium during the solid-to-liquid transition. After reaching the melting temperature of the SAT-AC CPCM at about 46 °C, the temperature continued to rise slowly until a complete phase change. The SAT-AC CPCM began to melt earlier than the SAT CPCM due to its lower phase-change

temperature. The solid-liquid phase-change of the SAT CPCM began at a nearly constant temperature of about 56 °C, and only two stages could be clearly detected in the temperature profile. The rapid temperature increase seen in the liquid phase was not found in the SAT CPCM because of the absence of the superheating phase.

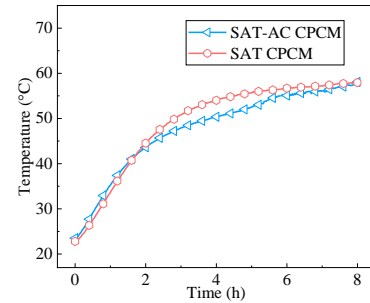


Fig. 6 Temperature variation of the unit containing different storage mediums during charging.

The temperature comparison of the storage mediums during the discharging process is presented in the following Fig. 7. The SAT-AC CPCM went through three stages. Initially, the temperature decreased rapidly as sensible heat was released from the liquid phase. The temperature decrease then slowed, indicating the onset of the liquid-to-solid phase transition. After releasing the stored latent heat, the temperature began to drop more rapidly again. In contrast, the SAT CPCM did not exhibit a clear liquid-solid sensible heat release stage due to relatively inadequate charging. The latent heat release phase of the SAT-AC CPCM lasted approximately 112% longer than that of the SAT CPCM. Consequently, a substantial portion of the thermal energy on SAT CPCM was released as sensible heat.

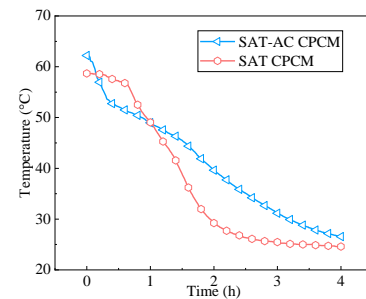


Fig. 7 Temperature variation of the unit containing different storage mediums during discharging.

The instantaneous efficiency of the SHC working with different storage mediums is compared in Fig. 8. All efficiency profiles show a similar trend, decreasing over time. After approximately two hours, the rate of efficiency decline for the SHC combined with the SAT-AC CPCM became lower than that for the SHC with the SAT

CPCM. This difference may be attributed to the varying phase-change temperatures of the storage mediums. The phase transition of the storage medium moderates the rise in HTF temperature, contributing to a more stable efficiency. A gentle improvement in the efficiency of the heating system was observed when using SAT-AC CPCM as the storage medium.

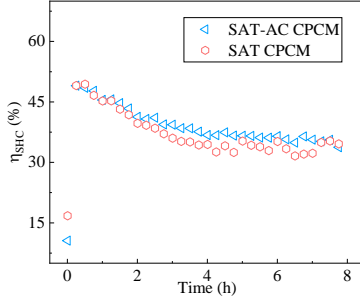


Fig. 8 Efficiency of the solar heat collector of the system containing different storage mediums.

It has been observed in Fig. 9 that the phase-change behavior of the PCM plays a vital role in the thermal performance of the heating system. Under the same operation condition, the inclusion of the SAT-AC CPCM demonstrated an improvement in the overall efficiency of the heating system compared to that containing the SAT CPCM. This improvement, which can reach approximately 5.3%, is attributed to the phase transition characteristics of SAT-AC CPCM.

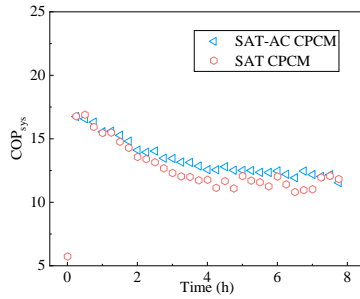


Fig. 9 Coefficient of performance of the heating system containing different storage mediums.

The drain water profiles of the SAT-AC CPCM storage unit and SAT CPCM storage unit are compared in Fig. 10. Both profiles show a similar trend: a rapid decrease in temperature during the initial discharging period, followed by a relatively steady level. The outlet water temperature extracted from the SAT CPCM storage unit decreased faster during the final exothermic period. The relatively insufficient heat charging shortens the effective heat release process. Conversely, the SAT-AC CPCM storage unit delivered more available heat during the discharging process. Despite having higher phase-

change enthalpy and density, the high melting-temperature PCM exhibited a lower phase-change fraction and released less latent heat thermal energy compared to the SAT-AC CPCM, which has a relatively lower melting temperature. These results indicate that a higher phase-change temperature in the storage medium can limit latent heat storage, thereby failing to achieve a consistent discharging process.

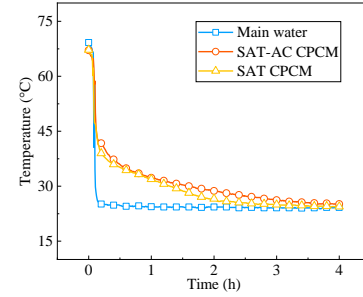


Fig. 10 Drain water temperature of the LHTES unit working with different storage mediums.

While the SAT CPCM could theoretically achieve a larger storage density due to its higher latent heat, no significant improvement was observed in system performance. The performance of the heating device in conjunction with a high phase-change range latent heat storage medium may be improved under more abundant solar radiation. In addition, low thermal conductivity was considered the major restriction of PCMs [12,13]. Improving thermal conductivity could enhance energy storage capacity during the charging process. The improvement in the overall heat transfer ability of the storage unit may expand the application potential of PCMs as storage materials for SHCs.

#### 4. UNCERTAINTY ANALYSIS

The experimental uncertainty of the test results was assessed based on the precision accuracy of each fabricated instrument. Assuming that the errors in thermophysical properties and the collection area were negligible, the uncertainty of the solar heating system was determined by using (3). It was found that the maximum relative uncertainty in determining the efficiency of the SHC was around 3.0%.

$$U_{\eta_{SHC}} = \eta_{SHC} \sqrt{\left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{U_{T_{out}}}{T_{out}}\right)^2 + \left(\frac{U_{T_{in}}}{T_{in}}\right)^2 + \left(\frac{U_I}{I}\right)^2} \quad (3)$$

where  $U_{\dot{m}}$ ,  $U_{T_{out}}$ ,  $U_{T_{in}}$  and  $U_I$  are the uncertainties of mass flow rate, temperature data, and solar radiation, respectively.

## 5. CONCLUSIONS

The thermal performance of the solar heating system with different storage mediums was experimentally compared. The LHTES units containing SAT-AC CPCM and SAT CPCM were assembled with the heating device to investigate the impact of the phase-change behavior on the system performance. The main conclusions of this study are summarized as follows: The solid-liquid phase change of the SAT-AC CPCM and the SAT CPCM occurred at 47.8 °C and 56 °C, respectively. The liquid-to-solid phase of the SAT-AC CPCM lasted about 112% longer than that of the SAT CPCM. A substantial portion of thermal energy was released in the form of sensible heat for the SAT CPCM unit. The decline rate of the efficiency of the SHC combined with the SAT-AC CPCM became lower than that of the SAT CPCM at the later charging stage. The COP of the heating system with SAT-AC CPCM was about 5.3% higher than that with SAT CPCM. Despite the higher phase-change area and phase-change enthalpy of the SAT CPCM, it presented a relatively lower molten fraction and provided less energy compared to the SAT-AC CPCM. The prototype and the design guidelines of the heating system were delivered for building applications. Future work should include a systematic analysis of the long-term energy and economic performance of the solar heating system with different storage mediums to determine the optimal system configuration.

## ACKNOWLEDGEMENT

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