Malaysian Journal of Chemistry, 2025, Vol. 27(3), 490-498
(Special Issue: *International Conference on Sustainable Materials and Technologies, ICSMT 2025*)

Analyzing Thermal Characteristics of a Salt-based Phase Change Material with the Addition of Nanoparticles

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The effective storage of thermal energy is essential for the progress of green energy systems. Sodium acetate trihydrate (SATH), a potential inorganic phase change material (PCM), is frequently constrained by its inadequate thermal conductivity and significant supercooling tendency. This work integrated nano-ZnO particles into SATH at different mass fractions (0–2.0%) to create nano-enhanced phase change materials (nano-PCMs) with increased thermal properties. The nano-ZnO/SATH phase change materials (PCMs) were analysed by differential scanning calorimetry (DSC), field emission scanning electron microscopy (FESEM), and thermal conductivity testing. The findings indicated that incorporating 1.0% mass of nano-ZnO significantly decreased supercooling from 35°C to 1.48°C and attained the maximum latent heat value (239.7 kJ/kg) across all tested nano-PCMs. Thermal conductivity demonstrated a steady increase with nanoparticle concentration, achieving a maximum boost of 27.96% at a 2.0% mass fraction. Increased nanoparticle dosage above 1.0% resulted in reduced latent heat capacity due to clustering phenomena. This study illustrates that optimised nano-ZnO incorporation may significantly boost the efficacy of salt-based phase change materials, with prospective applications in thermal energy storage systems necessitating improved heat transmission and thermal dependability.

Keywords: Sodium acetate trihydrate; PCM; nano-ZnO; thermal storage; characterization

Received: February 2025; Accepted: May 2025

The expanding need for effective thermal energy storage (TES) networks, propelled by the global shift towards alternative energy remedies, has positioned phase change materials (PCMs) as highly desirable options for preserving and releasing substantial thermal energy within confined temperature ranges [1, 2]. Their capacity to capture, retain, and discharge latent heat during shifts in phase renders them very appealing for uses including solar energy storage, waste heat recovery, thermal regulation in electronics, and temperature management in buildings [3, 4]. In the area of phase change materials (PCMs), inorganic salt hydrates, especially sodium acetate trihydrate (SATH), are very popular because they can store a lot of heat, handle many heating and cooling cycles well, and are affordable [5].

Despite these advantages, many intrinsic limits obstruct the actual implementation of SATH and other salt-based phase change materials in thermal energy storage devices. These encompass poor thermal conductivity, which limits the pace of heat transfer during charging and discharging phases, and supercooling behaviour, which may postpone the initiation of solidification [6]. Moreover, phase separation and material loss during phase shifts might undermine the prolonged durability of the PCM [7]. In order to solve these issues, scholars have investigated many augmentation approaches, notably the integration of nanoparticles into the PCM matrix to create nano-doped phase changing materials (nano-PCMs) [8, 9].

Nanoparticles, due to their elevated contact area-to-volume ratio and enhanced thermal characteristics, have the capacity to markedly enhance the thermal conductivity and durability of PCMs. Specifically, metal oxide nanoparticles like alumina, silica, magnesia, and titania have been extensively

†Paper presented at the International Conference on Sustainable Materials and Technologies (ICSMT 2025)

studied for such applications [10, 11]. Zinc oxide (ZnO) nanoparticles have garnered interest owing to their reasonable cost, chemical resistance, and elevated inherent thermal conductivity [12]. When evenly integrated into a PCM matrix, ZnO nanoparticles can establish conducting channels that enhance effective heat transport, therefore mitigating a primary drawback of conventional PCMs [13].

In the last ten years, multiple investigations have concentrated on altering the thermal characteristics of phase change materials by the use of nanoparticle additions [14, 15]. Thilak et al. [16] examined the impact of nano-silica on calcium chloride hexahydrate-based PCMs and noted improved thermal conductivity with slight reductions in latent heat. Anitha Selvasofia et al. [17] similarly exhibited enhanced temperature responsiveness in a paraffin-based nano-PCM system that incorporates eggshell nanoparticles. The enhancements were ascribed to the improved conduction channels created by the scattered nanoparticles.

Researchers have achieved considerable advancements in the domain of salt hydrate PCMs. Balasubramanian et al. [18] examined an inorganic salt hydrate utilising hybrid nanoparticle composed of silver and graphene. A substantial enhancement in the thermal characteristics of the inorganic PCM has been recorded due to the dissemination of hybrid nanoparticles.

Zhang et al. [19] investigated the thermal properties of SATH loaded with copper nanoparticles as nucleating agents and noted decreases in supercooling; however, the enhancement in thermal conductivity was minimal. Recent research by Yang et al. [20] has shown that the incorporation of multiwalled carbon nanotubes, carbon fibre, expanded graphite, and graphene into SATH enhanced thermal conductivity and mitigated phase separation by a particular amount. Nonetheless, the use of carbon-based materials may be economically unfeasible and present challenges with dispersion homogeneity and suitability.

The incorporation of ZnO nanoparticles into SATH remains inadequately examined in current literature, indicating a potential avenue for deeper investigation. Several first experiments have demonstrated encouraging outcomes from the integration of nano-ZnO with phase change materials (PCMs). Kumar et al. [21] investigated the impact of ZnO nanoparticles on a paraffin-based phase change material (PCM) and observed a significant enhancement in thermal conductivity and thermal endurance. Research by Wang et al. [22] demonstrated that nano-ZnO particles may markedly improve the thermal storage properties of palmitic acid in phase change material energy storage applications. Nonetheless, extensive research utilising SATH as the primary phase change material and ZnO as the additive, especially across various nanoparticle concentrations, is limited.

The dispersion technique and the quantity of nanoparticles are pivotal elements affecting the thermal properties of nano-PCMs. Higher amounts of nanoparticles usually improve thermal conductivity, but they can also clump together, which can harm the ability to store heat and the evenness of the mixture [23]. Consequently, it is essential to optimise nanoparticle concentrations to achieve a compromise between enhanced thermal efficiency and material durability. Research by Pasupathi et al. [24] on nano-enhanced phase change materials (PCMs) found that using 1.0–2.0 mass fraction loading provides the best balance between better heat performance and material strength, suggesting that a similar range might work well for ZnO-based nano-PCMs.

Another aspect frequently neglected in prior investigations is the comprehensive morphological and microstructural characterisation of the synthesised nano-PCMs. Field emission scanning electron microscopy (FESEM) provides information about nanoparticle dispersion and potential clustering, whereas differential scanning calorimetry (DSC) is the benchmark for assessing thermal transformations and latent heat values [24, 25]. Thermal conductivity analysers offer quantifiable data crucial for performance evaluation. Combining these complementary approaches allows a comprehensive understanding of the thermal and physical properties of nano-PCMs.

The current study aims to fill an important gap in knowledge by carefully examining the heat properties of SATH-based PCMs that have been improved with ZnO nanoparticles in amounts of 0, 0.5, 1.0, 1.5, and 2.0%. The research concentrates on the synthesis of nano-PCMs through a systematic dissemination approach, which is subsequently characterised through DSC for thermal analysis, FESEM for microstructural assessment, and a thermal conductivity tester for performance evaluation. The objective is to ascertain the way various concentrations of nanoparticles affect the latent heat, melting and freezing temperatures, thermal conductivity, and overall morphological structure of the PCM.

This research aims to enhance the field of TES materials by offering empirical perspectives on the development of sound, effective, and economical nano-inorganic PCMs. The work highlights sustainability and affordability by using SAT as the primary material because of its accessibility and low cost. The results will guide the future development and optimisation of nano-PCMs for thermal energy systems, particularly in situations requiring fast heat exchange and long-term dependability.

Figure 1. PCM and nanoparticle used in the study.

EXPERIMENTAL

Materials

The analytical grade sodium acetate trihydrate (SATH, purity ≥99%), an inorganic PCM was procured from Sigma-Aldrich for its high thermal stability and consistent phase change behavior. Zinc oxide nanoparticles (nano-ZnO) with an average particle size between 30 and50 nm, having purity of 99.9% were sourced from Ultrananotech. Carboxymethyl cellulose (CMC), a biodegradable thickener, had been bought from mymicrolab to mitigate phase separation in SATH. The deionized water was deployed as a solvent to dissolve CMC and ensure consistent mixing of the PCM. Figure 1 displays the photograph of SATH and nan-ZnO.

Preparation of PCM/Nano-PCM

The nano-ZnO/SATH PCM samples were synthesised by a straightforward mixing process. The appropriate quantities of SATH, CMC, and Nano-ZnO were assessed employing a high-precision weighing scale. The mass of SATH was established at 200g. The nano-ZnO at varying concentrations (0, 0.5, 1.0, 1.5 and 2.0%) were added into the PCM to obtain the samples with different composition. The total mass of CMC used in the experiment was 6 grams per 200 grams of SATH. The calculated SATH and CMC were put together in a glass container and stirred thoroughly. The container was thereafter placed in a hot plate at 75°C. Upon a thorough melting of the compound, the PCM was gently agitated and kept at a uniform temperature employing a magnetic stirrer operated at 600 rpm. Subsequently, the measured quantities of nano-ZnO had been uniformly diffused inside the PCM mixture. The solution was rapidly agitated using magnetic stirring for a further 60 minutes at 75°C to ensure adequate integration of the PCM and nano-ZnO particles preventing the formation of localized clusters.The mass fraction the nano-ZnO/SATH samples are given in Table 1.

Table 1. Mass fraction of inorganic PCM and nanoparticles.

Samples	Mass of nano-ZnO (gm)	Mass of SATH (gm)
SATH + 0% nano-ZnO	0	200
SATH + 0.5% nano-ZnO	1	199
SATH + 1.0% nano-ZnO	2	198
SATH + 1.5% nano-ZnO	3	197
SATH + 2.0% nano-ZnO	4	196

Characterization of Nano-MgO/PCM

The synthesized nano-ZnO/SATH composites were characterised using Field-Emission Scanning Electron Microscopy (FESEM), Differential Scanning Calorimetry (DSC), and a thermal properties analyser to evaluate their thermal behaviour and prospects as a thermal energy storage medium. The form and degree of distribution of nanoparticle were analysed using FESEM. The samples were fractured in chilled nitrogen, sputter-coated with gold to improve conductivity, and photographed at 5 kV under 1,000X scale.

Phase transition temperatures and latent heat values were determined utilising Differential Scanning Calorimetry (DSC). The samples, approximately 5 mg in weight, were enclosed in aluminium crucibles and underwent heating and cooling cycles ranging from 30°C to 80°C at a rate of 5°C/min in a nitrogen atmosphere. Three cycles per sample guaranteed repeatability, and data from the second cycle were examined to mitigate thermal history effects. The TEMPOS model thermal properties analyzer was utilized to assess the thermal conductivity of the samples.

RESULTS AND DISCUSSION

Figure 2 shows the FESEM micrograph of pure sodium acetate trihydrate (SATH) and SATH doped with nano-ZnO particles. Figure 2a shows a relatively smooth, well crystalline unaltered SATH surface. On the other hand, the nano-enhanced sample (Figure 2b) interconnects these smoothened white particles and the matrix through fine agglomerates of ZnO nanoparticles. The dispersion appears uniform and heterogeneous structure, probably because of the preservation of the nanoparticles by carboxymethyl cellulose (CMC), a thickener, that reduces clustering. The synthesis route by magnetic stirring is seen to be effective in the incorporation of the nanoparticles in the phase change matrix resulting in subtle but significant morphological changes.

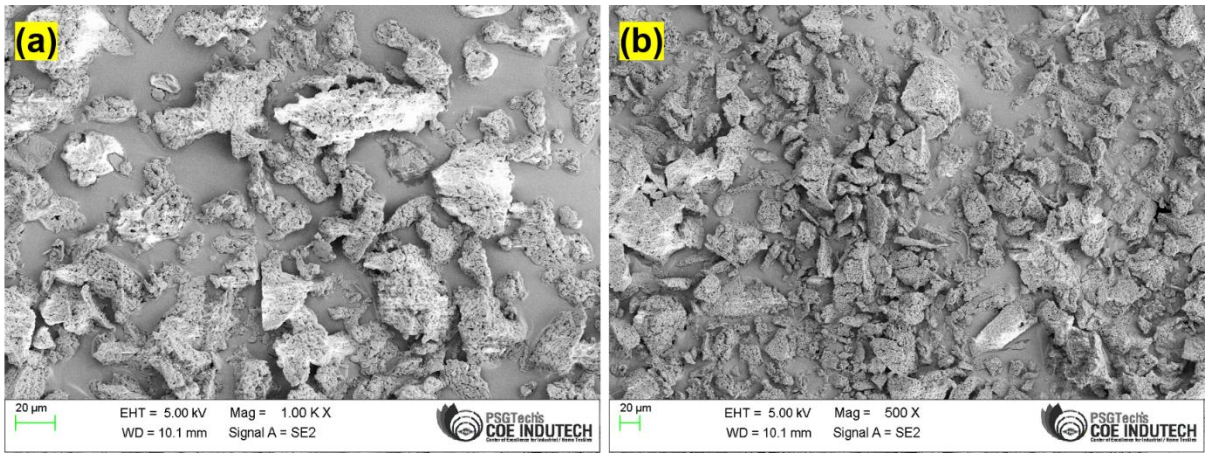

Figure 2. FESEM image of the (a) SATH (b) SATH + 1.0% nano-ZnO.

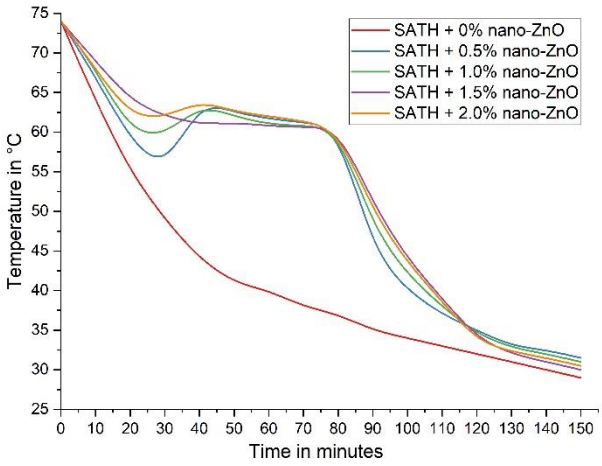

Figure 3. Cooling curve of SATH + nano-ZnO.

Table 2. Crystallization points and supercooling of SATH + nano-ZnO samples.

Samples	Lower crystal point (°C)	Upper crystal point (°C)	Degree of supercooling (°C)
SATH + 0% nano-ZnO	-	-	35
SATH + 0.5% nano-ZnO	54.08	57.63	3.55
SATH + 1.0% nano-ZnO	55.24	56.72	1.48
SATH + 1.5% nano-ZnO	52.38	58.86	6.48
SATH + 2.0% nano-ZnO	50.17	58.86	8.69

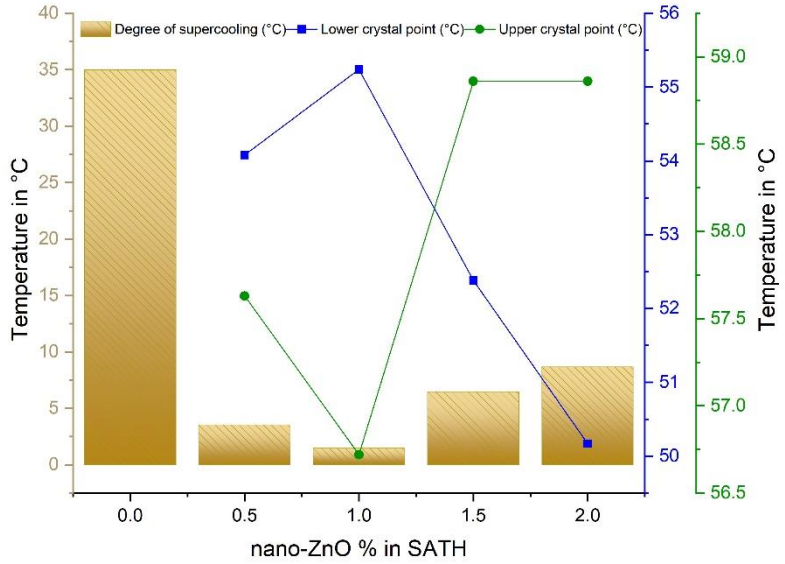

Figure 4. Degree of supercooling and disparity in crystallization temperatures of the samples.

The synthesized nano-ZnO/SATH composites had been analyzed to assess their thermal properties of the inorganic PCM at various concentrations of nano-ZnO. The experiments were conducted with three samples for each nano-ZnO/SATH PCM mixture to ensure result's reproducibility. The samples were initially placed into the in-situ fabricated PCM cylinders to assess their phase change characteristics during heat loss. In the experiment, each sample had been exposed to 75 °C, and the temporal temperature fluctuation was recorded to elucidate their phase transformation attributes while heat loss. The corresponding plot is presented in Figure 3. The cooling curve of the pure SATH seems to be flat and the PCM has come to equilibrium with the environment without liberating the latent heat. It can be attributed to its extreme degree of supercooling, which is in the order of 35 °C [26]. On contrast, in the nano-PCMs, nano-ZnO supported as the nucleating agent to liberate the stored latent heat in a controlled manner. Further, it is clearly seen that the increment in nano-ZnO mass fraction in the PCM positively curbed the supercooling of the SATH through the suppression of gap between lower and higher crystal points of the PCM until the rise of the nano fraction up to 1.0% and started falling thereafter. The details of the crystallization temperature and the supercooling of the PCM/nano-PCM samples are presented in Table 2.

Figure 4 illustrates the variations in supercooling, lower and upper crystal points with respect to nano-ZnO fractions. It can be clearly visible that the supercooling of the PCM has been drastically reduced from 35 °C to 1.48 °C at the mass fraction of 1.0% nano-ZnO in PCM. Thereafter, the supercooling was again raised with further increase in nano-ZnO fraction. In the similar pattern, the lower crystal point and the upper crystal points had also been varied with respect to nano-ZnO mass fraction in inorganic PCM. The upsurge in the supercooling at the higher loading of the nanoparticles can be ascribed to the possible aggregation reducing surface area availability for nucleation.

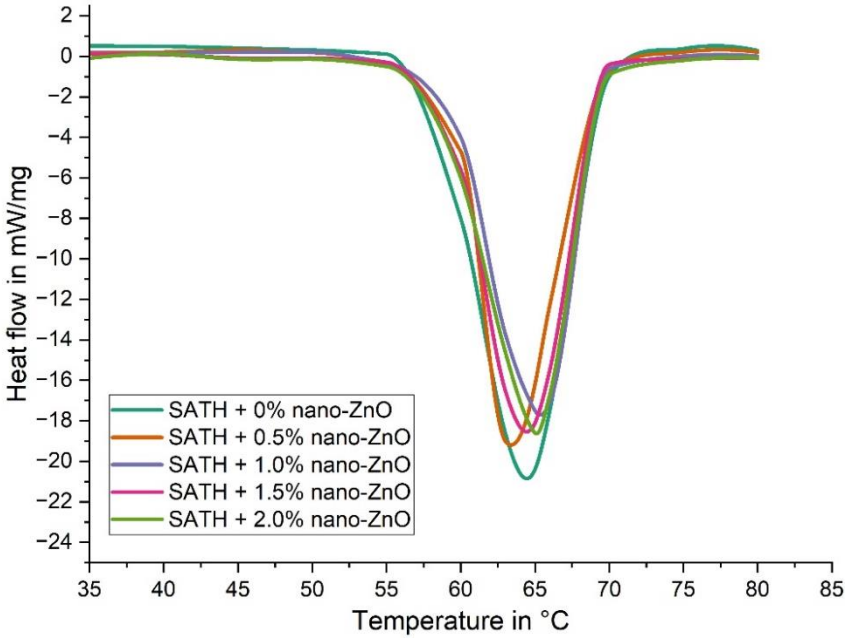

Figure 5. DSC of the SATH + nano-ZnO.

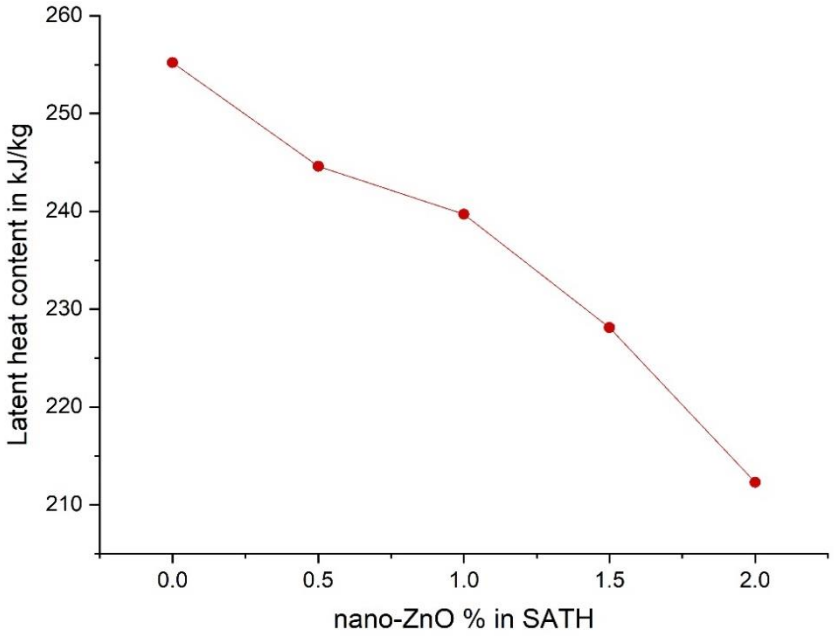

Figure 6. Latent heat values of SATH at different mass fractions of nano0-ZnO.

The thermal properties of the nano-PCM samples were analyzed through DSC, and the results are presented in the attached thermograms. For pure SAT, the melting point was found to be approximately 58.3°C, with a latent heat of fusion around 253 J/g. Upon the addition of ZnO nanoparticles, a slight shift in melting temperature was observed. Interestingly, the sample with 1.0% ZnO showed the highest latent heat among all the composites, suggesting an optimal dispersion and interaction at this concentration. However, further increasing the concentration to 1.5% and 2.0% caused a marginal decline in the latent heat values, potentially due to particle agglomeration disrupting the crystalline network of the PCM. These findings indicate that a moderate loading of nanoparticles enhances energy storage capacity, while excessive loading may hinder phase transition behavior.

The thermal characteristics of the nano-PCM samples have been investigated using DSC, and the findings illustrated in Figure 5. The melting point of

virgin SATH was determined to be around 58 °C, with a latent heat of melting about 255.2 kJ/kg. The incorporation of ZnO nanoparticles resulted in a minor alteration in the melting point. The sample containing 1.0% ZnO exhibited the least loss in latent heat across all composites (239.7 kJ/kg), indicating excellent dispersion and interaction at this state of concentration. Nonetheless, elevating the percentage of particles to 1.5% and 2.0% resulted in a considerable reduction in latent heat values, likely attributable to the accumulation of particles interfering with the crystalline structure of the PCM. The observations suggest that a moderate concentration of nanoparticles improves energy storage capability, whereas excessive concentration may impede phase shift behaviour.

Figure 6 outlines the disparity in latent heat storage capability among the samples with varying amounts of nano-ZnO particles. The latent heat of the inorganic PCM showed a negative correlation with the quantity of nanoparticle loading. The unaltered SATH initially showed a latent heat of 255.2 kJ/kg, which then dropped steadily to 212.3 kJ/kg at 2.0% nano-ZnO. The decrease can be linked to the dilution effect, in which non-phase-changing ZnO particles take up part of the composite PCM's mass, leading to a reduction in the actual SATH content.

Figure 7 illustrates the variation trend in thermal conductivity of the SATH with respect to nano-ZnO loading. Table 3 shows the percentage increment in thermal conductivity of the PCM with the upsurge in nano-ZnO concentration. The value of the conductivity steeply increased till 1.0% loading of the nano-ZnO. However, the slope of the curve is sharply decreased afterwards. The maximum thermal conductivity of the nano-ZnO/SATH is noticed as 0.819 W/mK (27.69% higher than base value) at 2.0% mass fraction of nano-ZnO. As a whole, the optimum fraction of nano-ZnO was identified as 1.0% considering different characteristic studies.

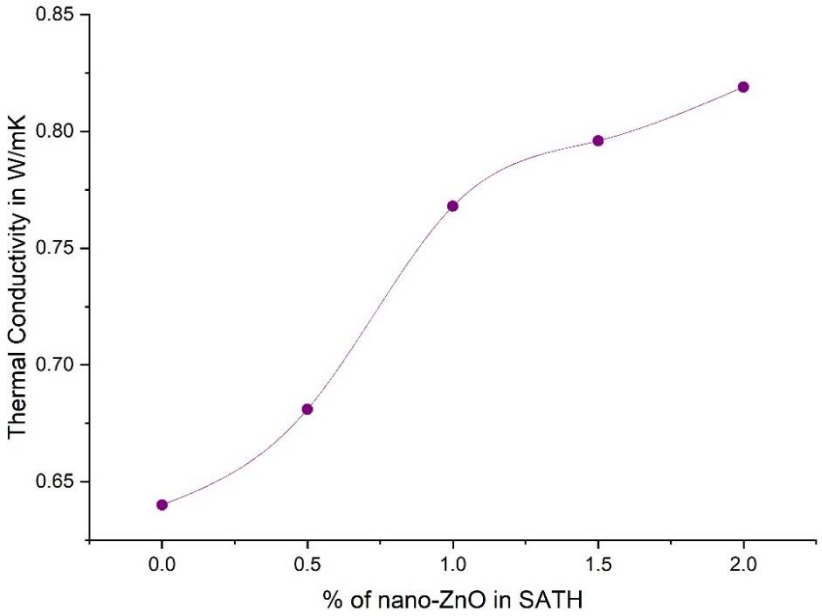

Figure 7. Thermal conductivity of SATH at different mass fractions of nano0-ZnO.

Table 3. Thermal conductivity of SATH + nano-ZnO samples.

Samples	Thermal conductivity (W/mK)	Thermal conductivity improvement (%)
SATH + 0% nano-ZnO	0.64	-
SATH + 0.5% nano-ZnO	0.681	6.4
SATH + 1.0% nano-ZnO	0.768	20
SATH + 1.5% nano-ZnO	0.796	24.38
SATH + 2.0% nano-ZnO	0.819	27.96

CONCLUSION

The present study investigated the thermal performance of sodium acetate trihydrate (SATH)-based phase change materials doped with nano-ZnO at varying mass fractions (0, 0.5, 1.0, 1.5, and 2.0%), focusing on the optimisation of nanoparticle concentration for enhanced energy storage efficiency. The key findings are given below:

- A 1.0 mass fraction of nano-ZnO was found to be the best amount to use, providing the best balance between higher thermal conductivity and maintained latent heat.
- The supercooling of pure SATH (35°C) was drastically reduced to 1.48°C at 1.0 mass fraction of nano-ZnO, highlighting the nanoparticles' nucleating effect
- The latent heat value of 239.7 kJ/kg at 1.0% loading is considered the optimum since it declines at higher concentrations due to nanoparticle agglomeration.
- Thermal conductivity improved with increasing ZnO content, achieving a 27.96% enhancement at 2.0%, though with some compromise in energy storage capacity.
- FESEM analysis confirmed uniform nanoparticle distribution at lower concentrations, supported by the stabilising role of carboxymethyl cellulose (CMC).
- Excessive nanoparticle loading beyond 1.0% disrupted the PCM matrix, leading to reduced thermal performance.

These findings suggest that nano-ZnO-enhanced SAT can be a promising candidate for thermal energy storage systems, especially where rapid heat transfer and minimal supercooling are critical.

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