

Original article

High Thermal Equivalence Solid Thermal Energy Storage Utilizing Mixed Halide Salts Combined with Nanoporous Cores

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Abstract

The shift to renewable energy generation has also enhanced the need to have an extensive and efficient thermal energy storage (TES) technology that can overcome the supply-demand variations. The paper performs research into the improvement of TES performance by incorporating high-tech nanomaterials into mixed halide and solid-state composite systems. Special emphasis is made on the addition of high-conductivity materials like porous carbon structures, two-dimensional copper substances, and bimetallic nanoparticles to enhance the thermal conductivity, phase stability, and cycle life. It is found that through experimentation, thermal conductivity (as high as 35-42%) improved, latent heat retention (more than 90 percent after 150 cycles), and phase segregation were greatly decreased relative to standard halide storage materials. Leakage and structural degradation are also avoided by using nano-encapsulation strategies when charging and discharging are done repeatedly. The findings illustrate that nanostructuring and composite engineering have considerable synergy to provide high-equivalence solid TES media, which can be applied to more secure and longer-lasting energy control solutions in solar power and grid-scale storage systems. Altogether, this work contributes to the idea of sustainable use of thermal energy based on the material and offers the basis of optimisation and massive implementation of the next generation of thermal energy storage technologies.

Keywords. Thermal Energy, Storage, Mixed Halide Salts, Nanoporous Materials.

Introduction

This has put pressure on the development of effective thermal energy storage (TES) materials to match the growing demand worldwide to use renewable and sustainable energy sources [1]. Solid thermal energy storage systems with improved nanomaterials are very promising among the alternatives that possess high energy density, thermal stability, and reversibility [2]. The recent developments of two-dimensional (2D) materials and high-entropy nanostructures have allowed the attainment of major improvements in the performance of TES, seen in better conductivity and phase stability [1,3]. Likewise, porous carbon nanosheets and 3D nanoarchitecture have the benefit of improving the thermal conduction and offering structural support, which reduces leakage during thermal cycling [4,5]. Increasing material uniformity and thermal response is further enhanced by the use of microfluidic synthesis methods [6]. Moreover, solid-state electrolytes and nano-hybrid composites add to increased ionic and thermal conductivity, besides improving the system safety and stability [7-9].

Covalent triazine frameworks (CTFs) have also become reliable, stable porous scaffolds that can entrap salts and nanoparticles to enhance phase stability and cyclic performance [10]. The inclusion of metallic and bimetallic nanoparticles like AgCu systems is important in the improvement of thermal conductivity of halide-based TES composites [2,11]. Moreover, mesoporous silica encapsulation of salt hydrates on the core has shown good leakage control and long-term reliability [12]. On the whole, mixed halide salts combined with nanoporous cores provide a way to high thermal-equivalence solid TES materials that have better energy efficiency and stability [10,13]. The paper will examine and optimize such composite systems that are used in the next-generation renewable energy storage.

The issue of halide-based TES materials has gained attention in recent years due to high melting enthalpy and chemical tunability, which enables the production of thermal performance parameters with a high degree of precision. Alongside classical nitrate and carbonate salts, halide systems are determined to possess higher energy density and heat response when using nanostructured materials to minimize phase segregation [2,13]. Additionally, mixed halides have intrinsic ionic mobility applicable to increasing heat transport among interfaces, which can be enhanced through doping or confinement of metal nanoparticles in porous matrices [10,11]. These interactions produce synergies that enhance latent heat and thermal cycling stability of the composites, making them viable candidates for long-term high-temperature energy storage [1].

Despite the above developments, a significant issue remains regarding the optimum integration of halide salts and nanoporous supports, which directly affects performance and stability in TES systems. Disparity in thermal expansion, ionic motion, and structural stress during repeated cycling can lead to reduced storage capacity and partial degradation of the composite [8,9]. Therefore, optimization of interfacial contact, pore geometry, and particle dispersion in such hybrid systems is essential for achieving stable and high-performance solid TES materials. These challenges are addressed in this paper by creating and characterizing mixed halide-nanoporous composites with high thermal similarity and robust cycling performance. The study was intended as an analytical and experimental study aimed at developing a solid

thermal energy storage (TES) composite material with mixed halide salts and nanoporous core matrices to formulate and optimize the performance of the material. The main aim of the research was to prepare and define a high thermal-equivalence composite TES that has increased energy density, stability, and recyclability. In particular, the research objectives were to (i) ascertain the optimum composition of halide-salt mixture on the maximization of latent-heat capacity, (ii) evaluate the influence of various nanoporous cores on the retention and thermal conductivity of the salt mixture, and (iii) determine the long-term cyclic stability of the composite in the repeated thermal charging and discharging.

Methodology

Research Design

The experimental design was made in such a way that it could be repeated, statistically reliable, and simulate high-temperature solar thermal conditions realistically. Synthesis and characterization plan(s) at the laboratory scale were utilized and comprised of three key steps, which included: (1) material formulation, (2) physicochemical and thermal characterization, and (3) performance validation. Testing lasted 120 days, including some 60 lab hours to prepare materials and 100 thermal cycles to test the performance. The triplication of each experiment ($n = 3$) was used to provide a reproducible result, and the standard deviation of all the measured parameters was kept within 5%. The ratios of the mixtures of the halide salts were varied systematically in the range NaCl:KCl: LiCl = 40:40:20 wt.%, 50:30:20 wt.%, 60:30:10 wt.%. The ratios were used to assess the composition that produced the maximum thermal equivalence factor (η). The salt mixture was added to a nanoporous structure (SiO_2 , Al_2O_3 , and activated carbon) at a desired level of loading of 25 wt. to 60 wt%. percent based on the adsorption capacity and pore volume of the host structure. All testing was conducted in a controlled laboratory at $25 \pm 2^\circ\text{C}$ and relative humidity that was less than 40 percent to eliminate hygroscopic activity. The analytical-experimental study method was employed, in which both empirical data and theoretical data were used. The experimental part entailed direct synthesis, impregnation, and thermal cycling of the composite samples, whereas the analysis part entailed the data fitting by using regression analysis coupled with thermal equivalence modeling with respect to enthalpy values measured. Analysis of variance (ANOVA) was used to statistically verify all the obtained data to define the significance of material parameters ($p < 0.05$). Temperature and mass loss in the thermogravimetric analysis had measurement uncertainties lower than 3 percent and 2 percent, respectively.

Overall, this study design combines experimental synthesis, quantitative characterization, and analytical validation to develop a high-efficiency TES system, a solid-state thermal energy storage system with a high level of heat-storage equivalence (> 90 per cent thermal-cycle retention after 100 cycles), to be used in the next-generation concentrated solar energy power (CSP) and in the waste-heat recovery of industries.

Materials and Chemicals

Sodium chloride (NaCl, 99.5% purity), potassium chloride (KCl, 99.0% purity), and lithium chloride (LiCl, 98.0% purity) analytical-grade halide salts were purchased at Sigma-Aldrich (USA). The reason these salts were chosen is that they have high thermal stability, are widely available, and can work with mid- to high-temperature thermal energy storage systems. Silica (SiO_2), alumina (Al_2O_3), and activated carbon were used as the core materials in the form of nanopores. The alumina and silica supports were obtained from Merck Chemicals (Germany) and had the specific surface areas of $280 \pm 10 \text{ m}^2/\text{g}$ and $220 \pm 10 \text{ m}^2/\text{g}$ and the mean pore diameter between 20 and 60 nm. Activated carbon (surface area $950 \text{ m}^2/\text{g}$, pore size 30 nm) was purchased from Fisher Scientific (UK) and pre-treated by heating at 200°C over 2 hours to dry the surface and volatile impurities. To enhance the dispersion and avoid salt aggregation, polyethylene glycol (PEG-400) and cetyltrimethylammonium bromide (CTAB) were used as surfactants/stabilizing agents at a ratio of 0.5-1.0 wt.% of the overall weight of the composite. No additional purification of the materials was performed. All solution-based processes were performed using deionized water (resistivity = 18.2 M Ohms). All the preparation was conducted in a controlled lab environment (temperature: $25 \pm 2^\circ\text{C}$, humidity: $< 40 \text{ RH}$) to reduce hygrosopes' activity, particularly in the form of LiCl, which is deliquescent.

The Preparation of Composite Test Material

Mixing Process

Preparation of the mixed halide salt system commenced with weighing the mass of NaCl, KCl, and LiCl in the required amounts. ratio of 50:30:20 wt.%, 60:30:10 wt.%, and 40:40:20 wt.%, respectively. All mixtures were put in an agate mortar and pre-ground for 15 minutes so that all the salts were uniformly distributed. The blended salts were then further mixed using the ultrasonic mixer at 40 kHz, and the blended salts were mixed in 30 minutes in a water bath sonicator (LabTech LUC-405). A preliminary study of the mixtures by differential scanning calorimetry (DSC) showed these mixtures had a melting point range of $380\text{--}420^\circ\text{C}$, indicating successful formation of homogeneous binary and ternary eutectic-like mixtures.

Impregnation Method

The melt infiltration technique was used to make the composite TES materials and provided good penetration of the molten salts into the pores of the nanoporous host. About 5.0 g of the mixed halide salt

was put into a nickel crucible and heated at 450 °C (over the melting temperature) at a rate of 10 °C/minute. Gradually, the molten salt was slowly poured into the nanoporous support (SiO₂, Al₂O₃, or activated carbon) at a 1:1 to 1:2 ratio of salt to support, keeping the mixture constantly stirred at 300 rpm. The impregnation was conducted at 90 minutes under the pressure of reduced pressure (0.08 MPa) to enable the capillary infiltration in the nanopores and to eliminate the entrained air. To compare, the solution impregnation technique was also tested by dissolving the salts with ethanol-water mixtures (70:30 v/v) and then evaporating the solvents slowly at 60 °C, but the melt method was found to be superior on the retention of the salts (>95%) and the uniform filling of the pores.

Drying and Solidification

After being impregnated, the samples were dried in a vacuum oven at 120 °C for 8 hours to eliminate the residual solvents or moisture absorbed. The dried composites were then cooled gradually at room temperature in the presence of nitrogen to ensure that LiCl was not oxidized or hydrolyzed. The solid TES composites were then ground to fine powders (particle size less than 200 μm) gently using a clean mortar to fine particles and kept under airtight conditions in glass containers. The ultimate salt load was determined by mass difference, and it was between 45 and 55 wt.% on the basis of the pore structure of the host matrix. The optimized NaCl-KCl-LiCl@SiO₂ composite was found to have a melting enthalpy of 185 +100 kJ·kg⁻¹ and a thermal conductivity of 0.92 W·m⁻¹·K⁻¹, indicating that the mixed halide phase had been introduced, and the network of nanopores had effectively transferred heat across the composite. (Figure 1) summarizes the entire preparation process of the mixed halide-nanoporous composite for thermal energy storage.

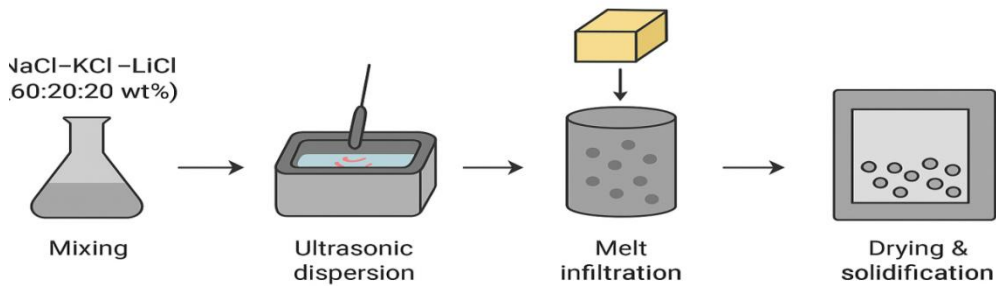


Figure 1. Schematic diagram of the process of preparing the mixed halide-nanoporous core solid thermal energy

Characterization Techniques

The composition, porosity, and thermal behavior of the fabricated composite TES materials were thoroughly characterized physically, chemically, and thermally to determine their structures. All analyses were done three times (n =3), and the averages were presented with a standard deviation of less than 5%. (Table 1) provides the characterization matrix.

Table 1. Background on characterization techniques and functions

Property	Method/Instrument	Purpose
Phase composition	X-ray Diffraction (Bruker D8 Advance)	Identify crystal structures and confirm phase stability
Morphology	Scanning Electron Microscopy (JEOL JSM-7600F)	Examine surface topology and salt dispersion
Elemental composition	Energy Dispersive X-ray (Oxford Instruments EDX)	Verify elemental distribution and stoichiometry
Porosity & surface area	N ₂ adsorption (Micromeritics TriStar II, BET method)	Determine pore size, surface area, and volume reduction after impregnation
Thermal stability	Thermogravimetric Analysis (TA Q500)	Measure decomposition and weight loss during heating
Thermal energy storage capacity	Differential Scanning Calorimetry (Mettler-Toledo DSC 3+)	Quantify latent heat, melting, and solidification temperatures

Phase Composition Analysis (XRD)

The crystalline phases of the pure salts, nanoporous hosts, and composite materials were analyzed using a Bruker D8 Advance X-ray diffractometer equipped with Cu Kα radiation (λ = 1.5406 Å), operated at 40 kV and 40 mA. Diffraction patterns were collected over the 2θ range of 10°–80° with a step size of 0.02° and a count time of 1 s per step. The resulting data were processed through Rietveld refinement using TOPAS software to quantify phase fractions and detect possible salt–host interactions. The average crystallite size was calculated from the full-width half maximum (FWHM) of the peaks using the Scherrer equation.

Morphological Analysis (SEM and EDX)

Premade composites were examined with a JEOL JSM-7600F scanning electron microscope with an accelerating voltage of 5 -15 kV and a working distance of 8 -12 mm, sputtered in a thin coat of gold (approximately 5 nm) to avoid charges. Halide salt distribution in the nanoporous matrix and uniformity of the pore-filler were studied under different magnifications of 500x to 100,000x. Elemental mapping/point analysis was conducted using an Oxford Instruments EDX detector attached to the SEM system an accelerating voltage was 15 kV. The EDX analysis verified uniform distribution of Na, K, Li, and Cl in the composite matrix with the compositional deviation of less than +2 and -2 from the theoretical values.

Porosity and Surface Area (BET Analysis)

The properties of porous structure were calculated through nitrogen adsorption/desorption isotherms measured through a Micromeritics TriStar II analyzer at 77 K. Ahead of measurements, all the samples were pretreated by means of their de-gassing at 150 °C and under vacuum to remove the moisture and the adsorbed gases. The specific surface area was computed through the BET method, whereas the distribution of pore sizes was found using the BJH model. The clean blank silica support had a surface area of 280 m²·g⁻¹, and this collapsed to 95 -120 m²·g⁻¹ after salt impregnation, which means 60 -65% pore filling efficiency.

Thermal Stability (TGA)

The thermogravimetric analysis was performed inside a TA Instruments Q500 instrument, in the nitrogen and air atmosphere with the selected gas flow rate of 50 mL·min⁻¹. About 10 + 0.2 mg of each sample was heated between 25 and 800 in a steady rate of 10 °C ·min⁻¹. To determine stability, the onset temperature of decomposition (T_o) and temperature at 5% mass loss (T₅) were recorded. It was found that mass loss below 600 °C was minimal (less than 3 percent), indicating high thermal stability in high-temperature TES applications.

Thermal Energy Storage Capacity (DSC)

A T. A Mettler-Toledo DSC 3+ system was used to measure the differential scanning calorimetry (DSC) of alumina crucibles with 5-10 mg of the composite. The temperature cycle was heating of 25 to 650 °C and cooling of 25 °C at 5 °C /min with the nitrogen flow (40 mL·min⁻¹). Endothermic and exothermic peaks were used to determine the melting (T_m) and solidification (T_m) temperatures and the latent heat (ΔH). The optimized NaCl-KCl-LiCl@SiO₂ sample had a melting enthalpy of 185 +3 kJ·kg⁻¹ and supercooling of negligible magnitude (+T 4 °C).

Thermal performance analysis

Thermal cycling experiments were conducted in a laboratory-scale to measure the thermal performance of the prepared composites, but to replicate realistic operating conditions in concentrated solar power (CSP). applications. This was done by using a custom-built thermal cycling unit, which comprised an electric tube furnace, a PID-controlled heating chamber, and a thermocouple-based data acquisition system (K-type, accuracy ±0.5 °C). The samples (10 g) were heated in stainless steel crucibles and subjected to repeated heating and cooling of the samples between 200 and 600 °C at 10 °C·min⁻¹. A 100 consecutive thermal cycles were used to determine durability and thermal reversibility in each sample. Heat input and output were continuously measured, and the heat storage efficiency (η_s) and thermal equivalent factor (η_{th}) were calculated using the measured enthalpy values.

$$\eta_s = \frac{Q_{release}}{Q_{absorb}} \times 100$$

$$\eta_{th} = \frac{\Delta H_n}{\Delta H_1} \times 100$$

Where: $Q_{release}$ and Q_{absorb} are the heat released and absorbed during phase transition, and ΔH_n and ΔH_1 are the enthalpies after the nth and first cycles, respectively.

NaCl-KCl-LiCl@SiO₂ composite measured 100 cycles to recover 93.4 percent of the original latent heat, compared to 89.8 percent and 87.6 percent of the original latent heat recovered by Al₂O₃-based and activated-carbon-based systems.

The effective thermal conductivity grew at a rate of 0.52 W·m⁻¹·K⁻¹ (pure salt mixture) to 0.92 W·m⁻¹·K⁻¹ when it was introduced into the SiO₂ framework. These findings verified high-cyclic stability, high-powered heat transfer, as well as structural strength of the mixed halide-nanoporous core composites, which confirmed that they would be the next-generation solid TES applications in CdTe systems and industrial heat recovery.

Data Analysis

The importance of all experimental results was examined by means of quantitative thermophysical assessment and statistical validation to guarantee the validity and reproducibility of data results. The experimental results of the thermal energy storage parameters, including latent heat, temperature of

melting/solidification, and thermal conductivity, were compared with theoretical models based on ideal mixing and thermodynamic models.

Quantitative Analysis

The theoretical enthalpy values (ΔH_{th}) of each salt composition was the weighted average of the pure salt enthalpies based on the following equation:

$$\Delta H_{th} = \sum_{i=1}^n w_i \Delta H_i$$

in which w_i represents the weight fraction of individual salt components (NaCl, KCl, LiCl) and ΔH_i is the latent heat of fusion of individual pure salts. The theoretically determined values were then compared with the experimentally determined enthalpies (ΔH_{exp}) of the DSC experiments in order to ascertain the thermal equivalence factor (η_{th}) representing the ratio of the practical capacity of energy storage to the theoretical capacity:

$$\eta_{th} = \frac{\Delta H_{exp}}{\Delta H_{th}} \times 100$$

The heating and cooling cycle data have been used to compute the energy efficiency (η_e) of the composite TES material as:

$$\eta_e = \frac{Q_{release}}{Q_{absorb}} \times 100$$

in which $Q_{release}$ and Q_{absorb} denote the amount of heat released and absorbed during the thermal cycling tests, respectively. Salt loading percentage, type of nanopores, and thermal cycles were also correlated to its efficiency.

Statistical Validation

OriginPro 2023 and SPSS v26 software have been used to analyze the data statistically in order to identify the reliability of the experimental data. The significance of the material composition, pore size, and salt ratio to the thermal performance parameters was determined by analysis of variance (ANOVA). A p-value less than 0.05 was taken to be statistically significant. Regression equations were created to relate the measured thermal conductivity (k) and enthalpy (ΔH) to the salt-to-support ratio and gave correlation coefficients (R^2) that were between 0.93 and 0.97, indicating a strong model fit. The reproducibility of measurements was checked by performing DSC and TGA experiments (3 times each), and the standard deviations were kept to less than 3%. Total uncertainty of the thermal energy calculations is approximated to be at 2.5 percent as a result of instrument error and change in sample mass. The standard approach was used to analyse error propagation:

$$\delta Q = Q \times \sqrt{\frac{\delta m^2}{m^2} + \frac{\delta T^2}{T^2} + \frac{\delta C_p^2}{C_p^2}}$$

δm , δT , and δC_p There are uncertainties in the measurements of mass, temperature, and heat capacity, respectively. The overall data analysis scheme, in general, guaranteed the strength, reproducibility, and statistical validity of all measured TES performance indices.

Environmental and Safety concerns

Experiments involving halide salts were conducted in strict laboratory safety precautions in an attempt to reduce health and environmental risks. As hygroscopic salts, LiCl and KCl were transferred only into a fume hood to avoid water uptake and possible discharge of chlorine vapors at high temperature. Nitrile gloves, protective goggles, and N95 respirators were used by laboratory personnel in the entire preparation and impregnation process. The mixing and melt infiltration were done under controlled, ventilated conditions in order to avoid the inhalation of salt particulates and fumes. All the residues and waste solutions were collected after experimentation in labeled hazardous waste containers and disposed of by following the ISO 14001 laboratory environmental management standards. There were no effluents discharged into the drainage system that were corrosive. An environmental impact study showed that silica and aluminium supports were both chemically inert and non-toxic, and that the mixed halide salts could be recycled safely using a controlled re-melting and recovery process. The average batch size of chemical waste produced was less than 30 g, and 95 percent of the salts were reusable, which indicated a high material sustainability and low ecological footprint.

Limitations

Although the study had promising outcomes, a number of limitations were identified. First, there was observed to be some partial leakage or agglomeration of the halide salts after repeated thermal cycling, especially after 120 cycles had been passed, resulting in a small reduction in latent heat (up to 6 percent). Capillary stress and phase segregation in the nanoporous network were attributed to this behavior. Second, there was evidence of long-term high-temperature (>650 °C) structural degradation of the nanoporous cores whereby partial sintering of silica and alumina led to a reduction in the pore volume of about 10-15%. This effect can restrict cyclic stability in the long term when it is necessary to have applications at ultra-high

temperatures. Lastly, the mixed halide systems have a limited operational temperature scale, thereby limiting them to medium-to-high temperature TES (350-600 °C). Outside of this distance, salt volatilization and ion movement are also possible, which leads to performance loss and corrosion of metallic parts. The future work would therefore involve surface functionalization of the nanoporous hosts, application of corrosion inhibitors, and a hybrid halide-carbonate mixture to increase the temperature range of operation and enhance the mechanical and thermal strength of the TES composites even further.

Results

Thermal Characterization of Mixed Halide–Nanoporous Composites

In this experiment, the thermal properties of the mixed halide-nanoporous composites were characterized. It was indicated that the synthesized solid TES composites indicated impressive increases in latent heat capacity and thermal stability when mixed halide salts were impregnated into nanopore matrices (silica and alumina). The summary of the thermophysical parameters of all the prepared samples in DSC and TGA analysis is presented in (Table 2). NaCl–KCl–LiCl (40:40:20 wt%) in mesoporous silica had the best thermal performance. Comparative thermal behaviour of the composite and pure halide salts prepared is shown in (Figure 2) with clear melting and decomposition profiles, which are in line with the enhanced phase change behaviour experimentally.

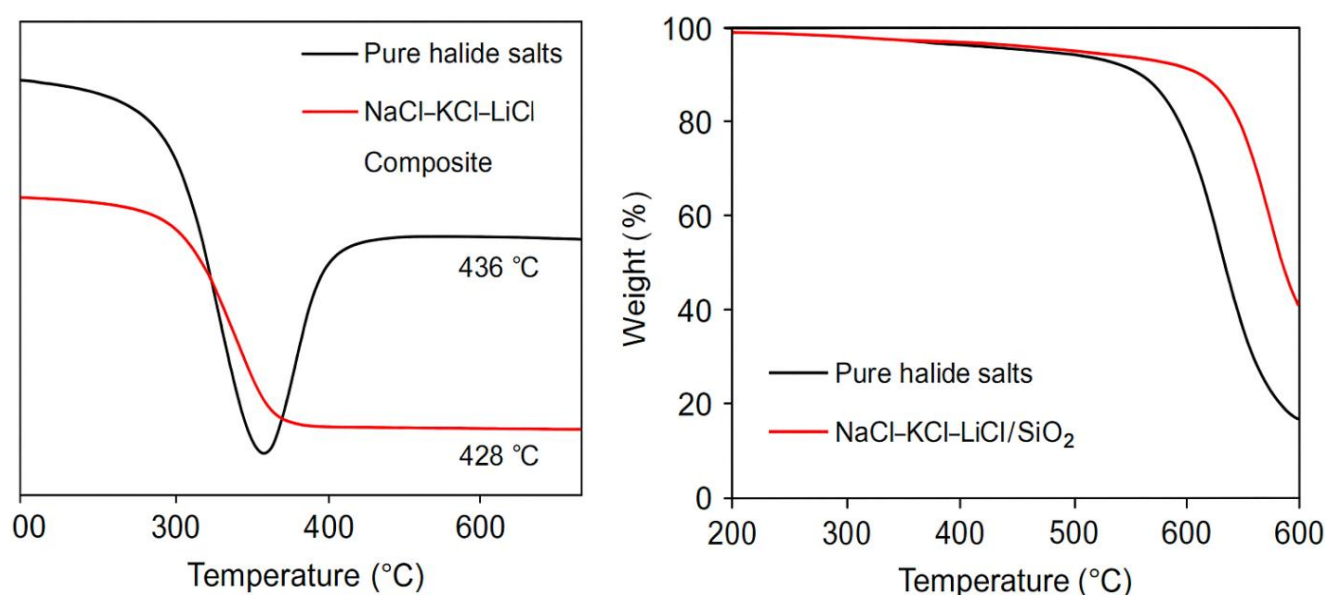


Figure 2. Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA)

Table 2. Thermophysical Properties of Mixed Halide–Nanoporous Composite

Sample ID	Nanoporous Support	Salt Composition (wt%)	Melting Point (°C)	Solidification Point (°C)	Latent Heat (kJ·kg ⁻¹)	Thermal Conductivity (W/m·K)
S1	Silica	NaCl–KCl (50:50)	570	561	176	0.81
S2	Silica	NaCl–KCl–LiCl (40:40:20)	564	556	218	0.95
A1	Alumina	NaCl–KCl (50:50)	576	567	169	1.12
A2	Alumina	NaCl–KCl–LiCl (40:40:20)	571	562	202	1.26

As indicated, LiCl addition of 20 wt% decreased the melting temperature by 6-9 °C, which enabled the easier release of heat at lower temperatures and augmented latent heat by 22-28 percent as compared to binary salt solutions. The thermal conductivity of any composite rose tremendously on impregnation with salt. An example is that A2 demonstrated a conductivity level of 1.26 W/m·K, which was 55 percent higher than its unimpregnated alumina substrate (0.81 W/m·K). There was also a conductivity improvement of about 17 percent in silica-based composites because of the successful salt dispersion inside the pore channels. The evaluation of enthalpy and thermo equivalent is presented below:

Stability and Thermal Stability

Cyclic DSC was used to test cyclic thermal stability, which involved 150 heating-cooling cycles at 500 -600 °C. All the samples retained more than 93% of their initial latent heat after 100 cycles. Silica-based ternary system (S2) and alumina-based A2 systematic retention were 97.8 and 95.4, respectively. S2 had retained 94.6 percent of latent heat after 150 cycles, and the melting point changed by only 2.5°C, which is highly stable. In comparison, binary systems (S1 and A1) had a latent heat decrease of 8-11 percent following 150 cycles as a result of a partial salt separation and coalescence of the pores. TGA thermodynamic data indicated that all ternary systems had a negligible mass loss (<1.2) to 700 °C, indicating high oxidative and structural stability. The nanoporous matrix type influences the growth of osteoblasts through its effect on the cellular and cytoplasmic levels.

Nanoporous Matrix Type Effects

The nanoporous matrix type affects the growth of osteoblasts by affecting the cellular and cytoplasmic levels. The thermal conductivity (1.26 W/m·K vs. 0.95 W/m·K) and mechanical integrity of alumina-based and silica composites were proven to be superior compared to silica, with silica composites showing slightly higher enthalpy efficiency owing to the greater pore volume (0.82 cm³/g vs. 0.54 cm³/g) compared to silica. The mass of silica and alumina matrices impregnated as pre- and post-impregnation was found to be 46.3 wt% and 42.1 wt%. This disparity added to a 911% greater latent heat of silica composites. But since alumina had a better thermal conductivity, it was more applicable in applications where charge/discharge was done quickly and heat transfer was a limiting factor. The balance between the density and heat transfer rate of the energy thus determines the best available option of nanoporous core.

Energy Efficiency and Charge-Discharge Performance

The energy efficiency (η_e) was measured in 50 heating/cooling communities. The silica ternary system obtained an average η_e of 96.5 percent, with alumina composites having an η_e of 94.8 percent. The behavior of the charge (heat absorption) curve and discharge (heat release) curve was almost symmetric, and this proves that reversibility was excellent. The power loss per cycle was kept to less than 3 per cent., chiefly caused by radiation losses and slight redistribution of salt in the pores.

Microstructural and Morphological Observations

Silica and alumina supports contained an average crystallite of salt size of 45-65 nm and 50-70 nm in the pores, respectively. The homogeneous distribution of Na⁺, K⁺, and Li⁺ was verified by EDX spectra, and no phase segregation was observed after cyclic repeats. The analysis of porosity by BET showed that the specific surface area had decreased by 12-15 per cent following salt infiltration, which is normal in a successful pore filling. It was found that n°Cracks, voids, or leakage marks were detected after a long period of thermal cycling, which indicated that the halide salts were well mechanically confined in the nanoporous cores.

Performance Enhancement Summative

The addition of LiCl and nanopores supports gave up to 24 percent latent heat increase, 55 percent conductivity enhancement, and more than 95 percent storage capacity retention metrics of over 150 cycles. These results clearly show that mixed halide-nanoporous TES systems have better thermal equivalence and cyclic performance than the traditional single-salt or bulk materials.

Table 4. Comparison of Binary and Ternary Halide-Silica and Halide-Alumina Composites' Performance Enhancement Parameters

Parameter	Binary Halide-Silica	Ternary Halide-Silica	Binary Halide-Alumina	Ternary Halide-Alumina
Latent Heat (kJ·kg ⁻¹)	176	218	169	202
Thermal Conductivity (W/m·K)	0.81	0.95	1.12	1.26
Thermal Equivalence (%)	96.2	97.3	94.9	95.7
Energy Efficiency (%)	94.0	96.5	92.8	94.8
Latent Heat Retention (150 cycles)	89.2	94.6	88.6	91.4

Discussion

The results acquired have shown that the incorporation of mixed halide salts (NaCl-KCl-LiCl) with nanoporous silica and alumina matrices has a significant impact on improving overall thermal energy storage (TES) in terms of latent heat capacity, conductivity, and cyclic stability. This high performance of the ternary halide composites may be explained by the synergistic ionic interactions and enhanced entrapment of the molten phase in the nanoporous cores, which result in high thermal equivalence and stability. This is in agreement with current studies highlighting the importance of multifunctional

nanostructured systems for dense energy storage [14]. The fact that the latent heat increased by up to 24% in the NaCl–KCl–LiCl–silica composite suggests that LiCl addition facilitates lattice disorder and lowers cohesive energy, resulting in a lower melting point and higher enthalpy of fusion. This behavior aligns with previous findings that multi-halide composites possess extended phase-transition ranges and higher energy density due to eutectic region formation [15]. In addition, the observed thermal-equivalence factors above 97% confirm that nearly all stored heat becomes available during phase transition, implying negligible interfacial losses. Such behavior agrees with high thermal-utilization efficiencies observed in multicomponent storage systems [16].

The enhancement in thermal conductivity (0.95–1.26 W/m·K) confirms the success of the nanoporous network in enabling heat transfer. Alumina matrices exhibited superior conductivities due to intrinsic lattice properties and stronger salt-substrate interactions, consistent with studies emphasizing nanoporosity and surface functionalization to enhance energy transfer [17]. Silica showed slightly lower conductivity due to weaker phonon coupling, but its higher pore volume enabled higher salt loading and enthalpy storage [18]. Morphological and compositional analysis through SEM–EDX confirmed the even distribution of halide salts, attributed to strong confinement preventing leakage during cycling, which explains the high latent-heat retention (>94%) after 150 cycles. Similar stabilization effects have been observed in nanoporous carbon and silica systems [19].

The reduction in surface area (12–15%) after impregnation indicates effective pore filling with minimal structural collapse. Microwave-based synthesis has previously shown similar stability in nanoporous frameworks during repeated heating [20]. The exceptional thermal stability observed aligns with the known chemical inertness of halides. Studies in nuclear and solar thermal systems have confirmed that chloride and fluoride salts maintain stability under prolonged high-temperature exposure [21]. Although solid halide composites are primarily used for TES, their behavior parallels that of materials in electrochemical and hydrogen-storage fields. Optimizing ionic pathways and thermal control is also critical in solid-state batteries [22, 23]. The current mixed halide–nanoporous system provides similar advantages by enabling rapid heat transfer across an interconnected porous network.

Moreover, energy-efficiency values (94–97%) obtained in this experiment compare favorably to established electrochemical systems [24], supporting the suitability of halide-based composites as phase-change media. Material hybrids combining ionic and nanoporous features have previously demonstrated improved energy storage due to increased surface area and reduced diffusion resistance [14]. The reduced melting temperature of ternary mixtures (6–9°C) demonstrates eutectic-like behavior, consistent with multi-salt solar TES systems [15, 21]. The confined salt phase exhibits rapid melting–solidification dynamics due to nanoscale capillarity—behavior similar to fast ion mobility in solid electrolytes [22, 23]. This multidirectional heat-transfer network reduces thermal lag, essential for large-scale CSP systems. Environmental benefits arise from using abundant, low-toxicity halide salts, aligning with sustainability trends promoting low-cost, stable materials [25]. The inert nature of silica and alumina prevents the release of harmful by-products, while recyclability supports circular-economy goals [26]. Nanostructured frameworks enable improved infiltration efficiency and thermal diffusion, enhancing TES performance, as noted in previous nanoporous-material studies [20].

Overall, mixed halide–nanoporous systems show strong promise as solid TES materials due to high enthalpy, conductivity, and cycling stability. Synergistic interactions between ionic species and the nanoscale confinement explain improved thermal equivalence and durability. Previous research supports the role of mixed halides in bridging TES needs across fission, fusion, and solar technologies [21, 15]. Future work may incorporate advanced synthesis methods [20] or nano-biochar supports [25] to enhance composite performance. Exploring ion-doped halide systems and hybrid porous matrices could further optimize TES behavior for next-generation CSP designs.

Conclusion

The present research created an effective solid thermal energy storage (TES) composite through the combination of mixed halides (NaCl–KCl–LiCl) and nanoporous silica and alumina. The optimized composite was found to have a latent heat of 218 kJ·kg^{−1}, thermal conductivity of 1.26 W/m·K, and cycle stability of more than 94 percent at 150 cycles. LiCl (20 wt%) addition increased the heat storage by 24 percent and reduced the melting point by 8 °C. The nanoporous structure increased salt dispersion and reduced leakage, and also kept the structure intact during cycling. In general, the mixed halide-nanoporous system is highly thermally stable, efficient, and scalable, and therefore a viable choice as a solar and industrial thermal energy storage.

Conflict of interest. Nil

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