Thermal Stability and Performance Evaluation of Hitec Molten Salt for High-Temperature Energy Storage Applications

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Abstract. The quest for advanced materials in thermal energy storage (TES) has become paramount in a world grappling with pressing demands for sustainable and reliable energy solutions. Among these materials, molten salts have emerged as up-and-coming contenders, owing to their exceptional thermal properties and wide operational temperature ranges. HITEC, a eutectic blend of sodium nitrate, sodium nitrite, and potassium nitrate, distinguishes itself as a superior choice due to its unique amalgamation of favorable thermal characteristics. This comprehensive review delves into the thermal properties of HITEC molten salt and its manifold applications in thermal energy storage, illuminating its potential as a pivotal element in addressing contemporary global challenges. The review examines HITEC's specific heat capacity, thermal conductivity, and thermal stability, presenting critical insights into its efficacy as a TES medium. Such comprehension fosters the advancement of Sustainable Development Goal 7. The article explores strides made in HITEC-based TES systems, underscoring inventive engineering approaches and burgeoning technologies that bolster progress towards Sustainable Development Goal 9. Furthermore, the article discusses challenges associated with HITEC molten salts, such as corrosion and material compatibility issues, and investigates ongoing research efforts to overcome these limitations. A comparative evaluation of HITEC with other molten salt mixtures elucidates its competitive advantages. This review consolidates knowledge about HITEC molten salt for thermal energy storage applications, providing valuable perspectives for researchers, engineers, and policymakers dedicated to advancing sustainable energy technologies. The review underscores the pivotal role of HITEC molten salt in advancing thermal energy storage technologies, directly influencing the achievement of several SDGs.

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1 Introduction

The global energy landscape is significantly transforming in response to climate change and the imperative for sustainable development [1,2]. The transition is gaining momentum with the utilization of renewable energy systems that harness energy from naturally replenishing sources such as sunlight, wind, water, and geothermal heat [3,4]. They provide electricity and heat for various applications, offering an eco-friendly and sustainable alternative to fossil fuels that deplete finite resources and emit greenhouse gases. Renewable energy systems have assumed a central role of utmost significance in the global effort to combat climate change and mitigate carbon emissions [5–7]. The primary sources of renewable energy include:

- **Solar Energy:** Solar power is a promise among renewable energy sources harnessed adeptly through innovative technologies such as photovoltaic cells and solar thermal systems. These cutting-edge mechanisms harness the boundless energy emanating from the sun, propelling humanity toward a sustainable future. Photovoltaic cells convert sunlight directly into electricity, whereas solar thermal systems use sunlight to make heat [8–10].
- **Wind Energy:** Wind turbines harness the kinetic energy of the wind to generate electricity, a practice that has gained widespread prominence. Onshore and offshore wind farms have increasingly proliferated, constituting a substantial portion of the global power supply [11,12].
- **Hydropower:** Hydropower systems generate electricity by harnessing the kinetic energy of flowing or descending water. Prominent examples of this innovative technology include large-scale dams, hydroelectric power plants, and reliable and uninterrupted renewable energy sources. These systems underscore the sustainable nature of hydropower, providing a continuous and dependable supply of electricity through the efficient utilization of water's natural energy [13,14].
- **Biomass Energy:** Biomass, derived from organic materials, can produce biofuels and biogas. Biomass energy is versatile and can be used for electricity generation, heating, and transportation fuels [15,16].
- **Geothermal Energy:** Geothermal energy harnesses the inherent heat within the Earth's crust. Utilizing this natural heat source, geothermal power plants can directly warm buildings and industrial facilities or transform them into electrical energy [17,18].

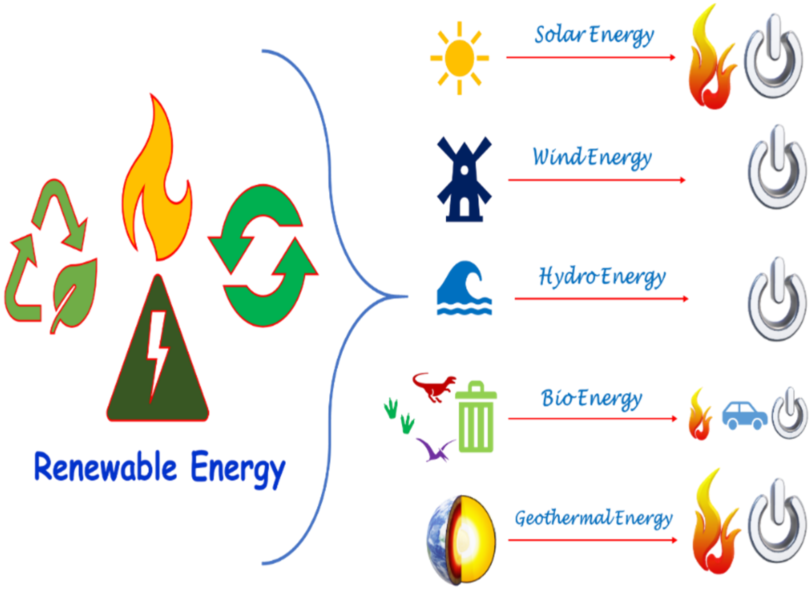

Fig. 1. Diverse Renewable Energy Sources.

However, it is challenging to satisfy steady energy demands since renewable energy sources such as solar, wind, and hydropower are sporadic because of weather conditions. Consequently, integrating energy storage systems has become imperative to address this issue. These systems help maximize the potential of renewables by mitigating their intermittent nature. These systems ensure a reliable energy supply, even when renewable sources are not actively generating power. They achieve this by storing surplus energy produced during peak hours. This storage capability stabilizes the variability in energy generation, leading to improved grid reliability and optimized energy utilization [19–21]. This review seeks to substantially contribute to the high-temperature applications field, specifically emphasizing solar energy storage. Its main goal is to advance Sustainable Development Goals (SDGs) 7 and 13 by advocating for environmentally responsible methods of harnessing and storing solar power. Ultimately, this research strives to lay the groundwork for a more sustainable and energy-efficient future [22,23].

In recent years, there has been a notable surge in enthusiasm surrounding thermal energy storage systems, specifically those that employ molten salts. The heightened interest stems from their extraordinary compatibility with high-temperature applications, such as concentrated solar power (CSP) [24–27]. One of its notable applications is in CSP plants, where molten salts are employed to enhance operational efficiency. Researchers in the field of solar thermal energy have been focusing their efforts on the development of molten salts and the improvement of their thermal properties. These molten salts predominantly comprise sodium and potassium nitrates, and they have been augmented with various additives to enhance their thermal storage capabilities [28–30]. The fundamental goal of this research project is to thoroughly investigate molten salts and their numerous uses in high-temperature environments. The study involves a detailed analysis of these salts' physical and thermal characteristics and investigating strategies for enhancing these properties. The existing literature reveals a scarcity of comprehensive reviews on molten salts and their evolution for high-temperature applications.

Furthermore, to the best of the authors' knowledge, a dearth of manuscripts comprehensively discusses various energy storage systems while focusing specifically on thermal energy storage, particularly regarding molten salts and their thermal properties.

Consequently, the objective of the current study is to fill this existing void by comprehensively examining the thermal characteristics exhibited by molten salts. This review offers a comprehensive and up-to-date understanding of recent advancements in molten salt thermal property enhancements, focusing on high-temperature applications. The review is structured into several sections, starting with an overview of different energy storage systems for renewable energy sources and then discussing thermal energy storage and various types of TES in Section 2. Section 3 delves into molten salts and highlights HITEC© molten salt for high-temperature applications. Finally, Section 4 presents the conclusions drawn from the comprehensive review.

2 Renewable Energy Systems

Contemporary energy grids rely heavily on Energy Storage Systems (ESS) to mitigate the inherent unpredictability of renewable energy sources such as solar and wind power. The primary function of ESS is to accumulate surplus energy generated during periods of high output and discharge it during peak demand periods. This intricate equilibrium effectively addresses the limitations imposed by the intermittent nature of renewable sources, ensuring a consistent and reliable energy supply. Moreover, they facilitate the seamless integration of additional renewable energy sources into the existing energy infrastructure, heralding a more sustainable future [31–33]. Here are some common types of ESS:

- Battery Energy Storage Systems (BESS) [34],
- Pumped Hydro Energy Storage (PHES) [35],
- Compressed Air Energy Storage (CAES) [36],
- Thermal Energy Storage (TES) [37],
- Supercapacitors [38],
- Superconducting Magnetic Energy Storage (SMES) [39],
- Hydrogen Energy Storage [40].

Apart from the above approaches, the ongoing scientific exploration delves into groundbreaking materials and technologies, including Mxenes, graphene-based supercapacitors, solid-state batteries, and advanced chemical storage solutions. These pursuits significantly enhance energy storage efficiency, capacity, and reliability [41,42]. These energy storage systems boast unique advantages and drawbacks, making them suitable for various applications and scales. Choosing the right system revolves around costs, efficiency, response time, and the specific requirements of both the renewable energy source and the grid infrastructure. As technology progresses, further developments and integration of these systems are expected, promising optimized utilization of renewable energy sources.

2.1 Applications of Energy Storage

The applications of energy storage are as follows:

- **Grid Stabilisation**: ESS helps maintain grid stability by providing frequency regulation, voltage support, and short-term energy backup during grid disturbances.
- **Renewable Integration**: ESS makes it possible to integrate sporadic renewable energy sources into the grid, reducing their fluctuation.
- **Electric Vehicles**: Batteries are crucial in EVs, allowing them to store energy for propulsion.
- **Residential and Commercial Backup Power**: ESS can provide backup power during outages in homes and businesses.

- **Industrial and Microgrid Applications**: ESS can be used in industrial facilities and microgrids to optimize energy use and reduce costs.

2.2 Challenges

The challenges regarding energy storage are:

- **Cost**: Energy storage systems can be expensive to deploy, but costs decrease over time.
- **Energy Density**: Improvements in energy density are needed to make ESS more efficient and cost-effective.
- **Lifecycle and Environmental Impact**: The production, operation, and disposal of ESS components can have environmental impacts.
- **Regulatory and Market Challenges**: The regulatory framework and market design often need to evolve to realize ESS's potential fully.

2.3 Thermal Energy Storage Systems

Thermal energy storage (TES) systems are cutting-edge technologies that efficiently store and control thermal energy for various applications such as heating, cooling, and power production. These systems are pivotal in promoting energy sustainability, reducing costs, and lessening the environmental impact of energy production and usage. TES stores surplus thermal energy when available and releases it as needed, balancing energy supply and demand. Among contemporary energy storage solutions, TES stands out due to its adequate heat energy storage and regulation capabilities. It is crucial for addressing energy management challenges, enhancing overall energy efficiency, and facilitating the seamless integration of renewable energy sources into the existing infrastructure.

Consequently, TES provides a versatile and sustainable approach to storing and regulating thermal energy, making it an indispensable component of modern energy systems [43–45]. The significance of the TES is depicted in Figure 2. There are several TES (Figure 3), each with advantages and disadvantages. Thermal energy storage systems are applied in various sectors, including:

- ***Building Heating and Cooling***: TES systems can store excess thermal energy during off-peak times (e.g., at night) and release it during peak demand hours, reducing heating and cooling costs.
- ***Solar Thermal Power Plants:*** Solar thermal power plants employ TES systems to capture surplus heat produced during sunny intervals and convert it into electricity when sunlight is unavailable.
- ***Industrial Processes:*** Many industries use TES to optimize energy-intensive processes, such as metallurgy, food production, and chemical manufacturing.
- ***Grid Energy Storage:*** TES can be integrated into the electrical grid to store excess electricity and release it when needed, helping to stabilize the grid and support renewable energy integration.

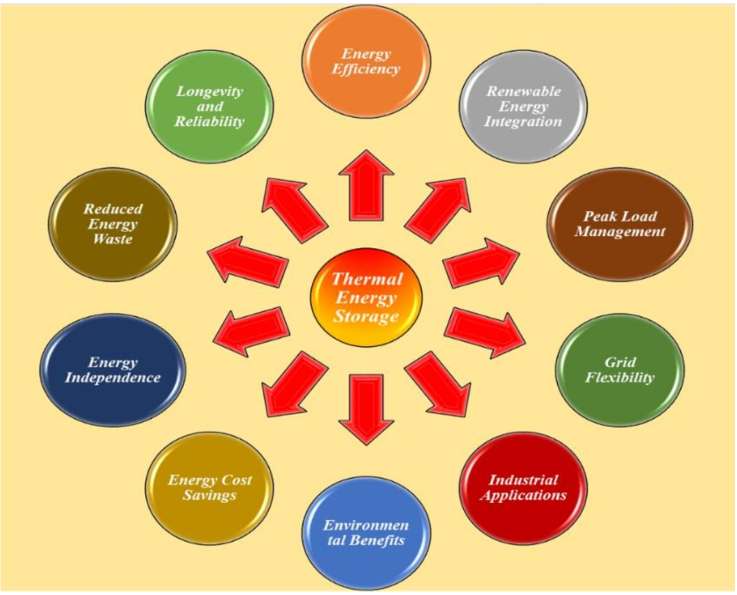

Fig. 2. Significance of Thermal Energy Storage.

1. ***Sensible Heat Storage*** [46,47]***:***
   - Sensible heat storage systems harness and retain thermal energy by altering a substance's temperature. Frequently employed materials for this purpose encompass water, pebbles, and concrete.
   - Energy is retained within a sensible heat storage system as the material absorbs heat and relinquishes it upon cooling. Examples include water heaters, heated water tanks, and hot water tanks used for space heating.
2. ***Latent Heat Storage*** [48,49]***:***
   - Latent heat storage systems harness energy by exploiting a substance's phase transition.
   - These systems commonly employ phase change materials (PCMs) like paraffin wax or salt hydrates. Latent heat storage systems boast a remarkable energy density, rendering them well-suited for deployment in both solar thermal power plants and passive solar heating applications.
3. ***Thermochemical Storage*** [50]***:***
   - Thermochemical energy storage devices collect and release heat through reversible chemical processes.
   - Examples include chemical reactions involving salts or metal oxides, which absorb heat during decomposition and release it during recombination. These systems can have high energy density and are often used in concentrated solar power (CSP) plants.

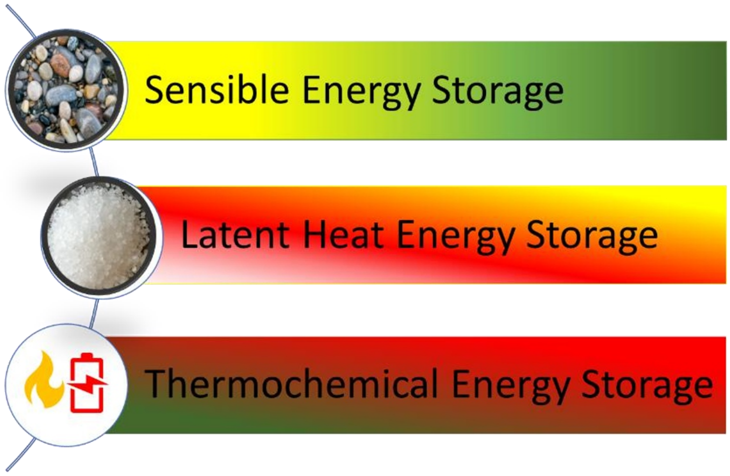

Fig. 3. Types of TES.

Thermal energy storage systems are pivotal in advancing energy efficiency, cost reduction, and the integration of renewable energy sources. They find application across various sectors, offering substantial advantages for sustainable energy management and environmental stewardship. As technology progresses, TES systems, particularly those based on molten salt, emerge as indispensable components for renewable energy and Concentrated Solar Power (CSP) plants. These systems rely on a blend of sodium nitrate and potassium nitrate, chosen for their remarkable capacity to retain heat at consistent temperatures. Molten salt maintains its liquid state even at high temperatures, rendering it an optimal medium for TES. Crucially, they address the intermittent nature of renewable sources by storing excess energy during periods of high production and releasing it during low-output times, such as overcast days or at night.

Molten Salt Energy Storage [51,52]***:***

- Molten salt energy storage technologies find widespread application in CSP installations.
- Molten salts with high-temperature properties, such as sodium nitrate and potassium nitrate, serve to store thermal energy. This ingenious system enables the prolonged retention of heat and the subsequent generation of electricity, even when there is no proper radiation.

3 Molten Salts-Based Energy Storage

Molten salt-based Thermal Energy Storage (TES) systems operate on a foundational principle. They utilize high-temperature molten salts as a medium to store thermal energy. During periods of energy surplus, such as from concentrated solar power or other heat sources, this excess energy is employed to elevate the temperature of the molten salt. The heated molten salt is then carefully preserved in well-insulated tanks or reservoirs. The hot molten salt is directed through a heat exchanger when energy is required, such as during nighttime or overcast conditions. This device transfers the stored thermal energy to a working fluid, typically water or another heat transfer medium, which propels a turbine or generates steam to produce electricity [30,52,53].

3.1 Thermal Property Enhancement of Various Molten Salts

TES has garnered considerable attention recently as a sustainable solution for storing and utilizing thermal energy. Molten salts have emerged as a promising choice for TES due to their advantages, including high energy storage capacity, exceptional thermal stability, and cost-effectiveness. However, the successful integration of molten salts in TES systems depends on thoroughly understanding their thermal properties.
It has been observed that the specific heat capacity of Hitec increases progressively with rising temperatures, highlighting its remarkable ability to absorb and release substantial amounts of thermal energy efficiently. Additionally, Hitec exhibits notably high thermal conductivity, further enhancing its effectiveness in facilitating efficient heat transfer. Collectively, these findings contribute valuable insights into the thermal properties of Hitec, supporting its potential application in TES systems.

Fernandez et al. [54] enhanced solar thermoelectric centrals' storage systems in this regard, significantly boosting renewable energy efficiency. Their research focused on the HITEC mixture (53% KNO_3, 40% $NaNO_2$, 7% $NaNO_3$) to improve solar salt for CSP plants. HITEC's lower melting point extends the temperature range for commercial solar plants (130-550°C). Fundamental properties tested include melting points, heat capacities, and thermal stability. Nitrite salts require protection with inert gas above 350°C to prevent oxidation by oxygen, a crucial challenge in their use. Iverson et al. [55] integrated molten nitrate salts to facilitate heat transfer and energy storage, focusing on variants such as solar salt, HITEC salt, and a composite nitrate blend of sodium, potassium, lithium, and calcium. Their investigation encompassed extensive material properties, including specific heat capacity, thermal expansion coefficient, thermal conductivity, latent heat of fusion, compressive and tensile strength, Young's modulus, and Poisson's ratio. Tensile strength was unaffected by temperature, while peak stress decreased, and Poisson's ratio increased with rising temperature. Understanding these properties is vital for addressing freeze events and optimizing phase change thermal energy storage. Boerema et al. [56] emphasize the crucial role of heat transfer fluid (HTF) selection in minimizing costs and optimizing efficiency in solar receiver systems. Comparing Hitec and liquid sodium as HTFs, they highlight sodium's advantages, like a broader operational temperature range and potential for advanced cycles. Liquid sodium's high heat transfer coefficient and lower heat capacity, though different from Hitec, make it a promising option for next-gen solar thermal power generation, pending solutions to its limitations. Zhong et al. [57] three distinct types of porous composite PCMs through the utilization of expanded graphite (EG) in conjunction with $LiNO_3$–KCl, $LiNO_3$–$NaNO_3$, $LiNO_3$–NaCl – binary molten salts employing a solution impregnation technique. The binary salt content ranged from 77.8% to 81.5%, with high encapsulation efficiency (72.8% to 78.8%). EG impregnation significantly boosted thermal conductivity (4.9–6.9 times). SEM images indicated improved homogeneity compared to other salt/EG composites. Importantly, these materials exhibited remarkable thermal stability over 100 cycles. Xiao et al. [58] developed a composite PCM by incorporating EG into a binary nitrate salts mixture ($NaNO_3$ and KNO_3, 6:4 ratio) using an aqueous solution method with ultrasonic assistance. The composite PCM exhibited improved thermal conductivity, reaching 4.884 W/(m K), while the total latent heat decreased by approximately 11.0%. Characterization techniques, including XRD, SEM, EDS, and TEM, confirmed EG's dispersion within the molten salts. This composite PCM holds promise for efficient TES applications. Li et al. [59] prepared a composite PCM by infiltrating a KNO_3/$NaNO_3$ (50:50 mol%) nitrate mixture into a SiC ceramic honeycomb (SCH) using vacuum infiltration. SEM images revealed even dispersion of the nitrate mixture within the porous SiC structure. DSC analysis indicated slight shifts in melting and freezing temperatures compared to pure PCM, with composite PCM having melting and freezing latent heat of 72.8 J/g and 70.3 J/g. The experimental findings conclusively indicated that elevating the mass fraction of SCH amplified both the rates of heat storage and heat release. This augmentation resulted in a remarkable reduction of 52.8% in the time required for heat storage and a substantial 58.3% decrease in the time needed for heat release compared to using pure PCM.

Seo et al. [60] aimed to examine how SiO_2 nanoparticles of different sizes influence the specific heat of a ternary nitrate salt eutectic comprising $LiNO_3$, $NaNO_3$, and KNO_3 when incorporated at a concentration of 1% by weight. This eutectic is valued for its thermal energy storage properties. Surprisingly, despite the low nanoparticle concentration and lower specific heat than the eutectic, the mixture exhibited a 13–16% increase in specific heat. The augmentation observed can be ascribed to developing nano-sized structures enveloping the nanoparticles. This phenomenon leads to a significant augmentation in the specific surface area, thereby amplifying the influence of surface energy on specific heat. Shin et al. [61] reported a significant increase in the specific heat capacity of a eutectic salt mixture when a 1% mass concentration of alumina nanoparticles was dispersed. A eutectic blend comprising lithium carbonate and potassium carbonate in a molar ratio of 62:38 was dissolved in distilled water. To this solution, 10 nm alumina nanoparticles were added, resulting in a mass concentration of 1.0%. The specific heat capacity of this mixture was meticulously investigated using a state-of-the-art differential scanning calorimeter (DSC). The research proposed an innovative model centered on in situ phase transformations, impeccably aligned with the experimental findings. These salt nanofluids hold promise for efficient thermal energy storage systems, potentially reducing solar power costs. Ho et al. [62] conducted a study to ascertain the optimal concentration of alumina nanoparticles within doped molten Hitec, aiming to maximize its specific heat capacity. A simplified interfacial area model was devised to elucidate the optimal concentration. Utilizing a differential scanning calorimeter, researchers conducted measurements to determine the specific heat capacities of the pure Hitec fluid and a nano-enhanced variant called nano-Hitec. Scanning electron microscopy was employed to examine microstructures post-solidification. Their findings identified an optimal concentration of 0.063 wt.%, resulting in a 19.9% enhancement in specific heat capacity. At 2 wt.%, nanoparticles had a detrimental impact on specific heat capacity, exceeding predictions. SEM images confirmed even nanoparticle dispersion at concentrations below 0.016 wt.%, with significant agglomeration at higher concentrations. The optimal concentration coincided with the point where isolated particles and clusters (0.2 to 0.6 μm) contributed equally to specific heat capacity.

Myers et al. [63] delved into the possibilities of molten salts serving as heat transfer fluids (HTFs) and thermal storage materials in high-temperature concentrating solar power (CSP) systems. Their focus was on augmenting the thermal conductivity of these salts, leading them to explore the incorporation of cupric oxide (CuO) nanoparticles into nitrate salts such as potassium nitrate, sodium nitrate, and a potassium-sodium nitrate eutectic mixture. Their study examined thermophysical properties, including thermal diffusivity and latent heat, and assessed chemical stability through temperature-variant FTIR spectroscopy. The research demonstrated improved thermal performance and chemical stability, making these enhanced nitrate salt systems promising for CSP applications. Madathil et al. [64] discussed the increasing importance of solar energy within the contemporary energy sector. This study aims to augment their thermal conductivity and specific heat capacity by optimizing the integration of MoS2 and CuO nanoparticles into molten salts. This research demonstrates the potential to create stable, salt-based heat transfer fluids for CSP plants. Additionally, it notes the minimal nanoparticle sedimentation compared to organic heat transfer fluids. Deng et al. [65] developed a novel potassium nitrate (KNO_3)/diatomite shape-stabilized composite phase change material (SS-CPCM) via mixing and sintering. KNO_3 was the phase change material (PCM), while diatomite was a structural support and leakage prevention matrix. Approximately 65 wt% of KNO_3 was effectively retained within diatomite pores and surfaces. X-Ray diffraction and FTIR spectroscopy established their compatibility.

After 50 thermal cycles, the melting and freezing temperatures altered slightly while latent heat decreased, making the KNO_3/diatomite SS-CPCM a promising candidate for TES in solar power plants.

Luo et al. [66] developed a one-step method to enhance TES in CSP plants. They synthesized nano-salts by decomposing copper oxalate into CuO nanoparticles within a binary salt, boosting specific heat by 7.96% in solid and 11.48% in liquid phases. The study revealed needle-like intermediate layers, explaining the heat enhancement. Increasing CuO concentration reduced latent heat and onset temperature while widening the melting range, maximizing TES efficiency. Ho and Pan [67] studied the impact of nanoparticle concentration on laminar convective heat transfer in a mini-circular tube using molten nano-HITEC fluid. They developed a novel apparatus and preparation process to prevent nanoparticle precipitation during measurement. The research revealed that incorporating nanoparticles at a 0.25-weight percent concentration led to a notable 11.6% rise in the mean Nusselt number. Similarly, at a lower concentration of 0.063 weight percent, an impressive 9.2% enhancement was observed, all without any precipitation. Furthermore, a novel correlation was established, significantly improving the accuracy of predicting heat transfer performance. These findings strongly indicate the potential of utilizing nano-HITEC fluid containing up to 0.25 weight percent alumina nanoparticles for adequate thermal storage.

Jiang et al. [68] introduced a form-stable composite PCM comprising $LiNO_3$–$NaNO_3$–KNO_3–$Ca(NO_3)_2$ and calcium silicate via cold compression and sintering. XRD analysis confirmed their chemical compatibility. This composite material exhibits a shallow melting point of 103.5°C, maintaining stability even under high temperatures, up to 585.5°C. It has demonstrated exceptional resilience through a rigorous test of 1000 melting and freezing cycles. Furthermore, its impressive thermal conductivity, measured at 1.177 Wm^{-1} K^{-1}, suggests significant potential for further enhancement. SEM revealed its microstructure, while DSC measured latent heat and heat capacity. Tian et al. [69] investigated NaCl–$CaCl_2$–$MgCl_2$/EG composites for solar TES. They used differential scanning calorimetry to study heat capacity and latent heat storage. Composites with 150-250 g/L EG and 0-5 wt% EG were prepared. The heat capacity of the solid composite exhibited a reduction as both the EG fraction and temperature increased. Liquid state heat capacity peaked at 1 wt% EG, rising with temperature. Melting temperatures remained constant, but latent heat decreased with EG. Composite thermal conductivity was 1.35-1.78 times higher than pure chloride. Liu et al. [70] developed a composite PCM using molten salt, EG, and graphite paper (GP). By varying GP content and compression degree, they optimized $MgCl_2$-KCl/EG/GP chunks. Increasing GP improved thermal conductivity but lowered latent heat beyond a 0.88 GP/EG ratio. Higher EG packing density enhanced conductivity until 280 kg/m³, where latent heat peaked. The best-performing block, with 0.84 GP/EG ratio and 280 kg/m³ density, displayed 205.35 MJ/m³ enthalpy and 12.76 W/m K conductivity, proving excellent thermal reliability for practical applications. Villada et al. [71] investigated novel molten salt mixtures for use in concentrated solar power. They compared commercial Hitec with ternary mixtures containing lithium nitrate, studying their thermal and rheological properties. The new mixtures exhibited a significantly lower melting temperature, improved heat capacity, and reduced viscosity near the solidification point. These findings suggest that despite the cost of lithium nitrate, the new molten salt mixtures offer promising prospects for thermal energy storage systems, potentially reducing capital costs due to their more comprehensive operational temperature range. Villada et al. [72] examined the long-term corrosion performance of SS304 stainless austenitic steel when exposed to three different molten nitrate salts: Solar Salt, Hitec, and a quaternary salt (45% KNO_3 - 34% $NaNO_2$ - 15% $LiNO_3$ - 6% $NaNO_3$). They conducted SEM/EDX and XRD analyses after a 2000-hour corrosion test. Additionally, the team used DSC, TGA, and Raman microscopy to assess these salts' melting behavior, thermal stability, and chemical changes. The study contributes to understanding material compatibility and optimizing engineering design for TES with molten salts.

Lincu et al. [73] highlighted the significance of efficient high-temperature TES for industrial waste heat utilization and continuous solar power generation. Researchers successfully engineered shape-stabilized phase change materials using mesoporous aluminosilicates and a eutectic mixture of $NaNO_3$ and KNO_3 molten salt. Incorporating aluminum doping bolstered thermal stability, elevating it to 550°C. The composites displayed two discernible phase transitions, and their nanoconfined phase properties were investigated. These materials demonstrated a significant latent heat storage capability ranging from 76 to 77 Jg−1, with 8 Jg−1 associated with the nanoconfined phase. Introducing aluminum dopants emerged as a promising approach for enhancing high-temperature thermal energy storage, augmenting the total heat capacity by 36%. Aljaerani et al. [74] researched improving TES materials in CSP plants. Researchers successfully synthesized a groundbreaking composite material by integrating Titanium Dioxide nanoparticles with a ternary nitrate molten salt called HITEC. The nanoparticle concentrations were varied during the synthesis process. The resulting composite, referred to as nano-enhanced molten salt (NEMS), underwent comprehensive characterization to assess its compatibility, nanostructure, and thermophysical properties. The study revealed noteworthy outcomes: adding 0.1 wt% TiO2 nanoparticles substantially enhanced HITEC's specific heat capacity, increasing it by 5.5%. Furthermore, the latent heat of the composite material saw a remarkable boost of 78%. Notably, the upper working temperature of the composite was elevated by 5% due to this integration. Morphological analysis confirmed well-dispersed nanoparticles and nanostructure formation, while FT-IR analysis indicated chemical stability. Thermal cycling tests demonstrated stability in both chemical composition and enhanced thermophysical properties. Liang et al. [75] investigated the solid-liquid interface between molten salt and solid oxides, a critical aspect for optimizing heat storage and transfer in CSP systems. Utilizing advanced molecular dynamics simulations, they delved into the thermal transport mechanisms at the MgO and molten Hitec salt interface. Their study illuminated the pivotal role played by highly organized ion adsorption structures of molten salt on the MgO surface in enhancing thermal transport. Furthermore, they underscored the significance of incorporating this interfacial thermal transport aspect when predicting the properties of molten salt nanocomposites for CSP applications.

Sumair et al. [76] explored the impact of dispersing graphene nanoparticles at different concentrations (0.01, 0.05, and 0.1 wt. %) into a eutectic salt mixture composed of various components. Their findings revealed an increase in heat capacity by 5% to 13% and a marginal 3% rise in thermal conductivity as graphene concentration increased. Saranprabhu and Rajan [77] undertook experiments to enhance the thermophysical properties of solar salt, which plays a vital role in the context of Thermal Energy Storage. They investigated the impact of incorporating 0.5 wt% MWCNTs through ultrasonication and milling. Results indicated an 18.3% enhancement in thermal conductivity and 18% in specific heat. The composite also increased energy storage capacity by 11.5% within the 50–270 °C range. These findings suggest potential applications of MWCNT-solar salt composites in thermal energy storage systems.

Zou et al. [78] introduced a pioneering quaternary nitrate molten salt, incorporating Hitec salt and $Ca(NO_3)_2$ as an additive. This distinctive composition is distinguished by its affordability, modest melting temperature, and remarkable decomposition threshold. The study measured fundamental thermophysical properties, revealing melting, crystallization, and decomposition points at 83.1°C, 163.1°C, and 628.5°C, respectively. This salt exhibited a broad working temperature range (200–565°C), surpassing Hitec salt and solar salt. Furthermore, it displayed enhanced specific heat (1.52 J/g K) and thermal conductivity (0.655 W/m K), leading to superior heat storage and transfer capabilities. The Hitec salt with

$Ca(NO_3)_2$ additive demonstrated excellent thermal stability during extensive testing at elevated temperatures. Ibrahim et al. [79] emphasize solar power's potential for sustainable energy. Solar Salt (KNO3-NaNO3) has been vital in CSP plants despite corrosion and low heat capacity issues. The authors propose exploring alternative salt mixtures (chlorides, fluorides, carbonates) with more comprehensive thermal stability and improved properties. Isaz-Ruiz et al. [80] studied high-temperature alumina nanofluids containing 0.5-1.5 wt% of 13.6 nm alumina nanoparticles. They assessed particle size, colloidal stability, and rheological behavior. The results showed intermediate size and stability, with nanofluid properties maintained even after an hour of static conditions. Viscosity-temperature relations followed established models, with Newtonian behavior observed in Hitec and molten salt-based nanofluids with 0.5 wt% Al_2O_3. The Chandrasekar model best represented the influence of nanoparticle concentration on viscosity. Vaka et al. [81] conducted thermal analysis on a binary mixture of $Al(NO_3)_3$ and $Cu(NO_3)_2$ with varying ratios, finding a eutectic temperature of 65°C. They also measured degradation temperature, specific heat, latent heat of fusion, and thermal stability. Using Design of Expert v13, they optimized compositions (60:40, 50:50, 55:45, and 57.5:42.5) and exposed them to high temperatures for 120 hours. The binary salt mixtures exhibited decomposition at 215°C. The optimal 60:40 Al/Cu ratio showed the highest specific heat, making it promising for solar applications. Field emission scanning electron microscopy confirmed a uniform salt distribution.

Parida and Basu [82] highlighted the importance of molten salt's high specific heat capacity (CP) in concentrated solar power plants. They investigated scalable methods for doping nanoparticles into molten salts, focusing on HITEC due to its lower melting point. DSC tests showed varying CP effects for alumina and silica nanoparticles, while T-history tests indicated different bulk-CP results. A Mann–Whitney U test revealed statistical differences between small and large batch CP values. For practical applications, both DSC and T-history methods should be employed to assess nanocomposite CP accurately. Xiao et al. [83] conducted experiments on HITEC salt ($NaNO_2$-NaO_3-KNO_3) and solar salt (NaO_3-KNO_3), which are commonly used in concentrated solar power. They added nanoparticles to enhance thermo-physical properties, measuring viscosities at various shear rates (200-450 ºC for HITEC and 250-500 ºC for solar salt). Results confirmed Newtonian behavior for pure salts. With 1% or 2% Al_2O_3 nanopowder or graphene, HITEC salt's viscosity changed slightly (-35.4% to 8.1%), while solar salt showed significant variation (-9.2% to 68.1%). Graphene notably increased viscosities in salts, causing slight non-Newtonian behavior in HITEC salt. Lambrecht [84] studied solar salt mixtures, assessing their life cycle and economic performance. Their innovative calculation method aligns with previous research, allowing for economic trends in different fluid usage scenarios within a standardized plant configuration. Future research should enhance accuracy by accounting for component size variations and monetizing fluid effects on materials, potentially extending plant lifetimes and electricity generation revenue. Ji et al. [85] have pinpointed HITEC molten salt as an exceptionally efficient heat transfer fluid for CSP, specifically for applications like parabolic trough collectors (PTC) and evacuated tube solar collectors (ETSC). Through meticulous experimentation involving the manipulation of HITEC's temperature and mass flow rates in ETSC, they observed significantly reduced heat loss compared to other tube systems. Moreover, the team successfully developed a novel empirical heat transfer correlation equation tailored for HITEC in ETSC. Notably, this equation exhibited a minimal deviation of ±19.2% from the actual experimental data, showcasing its accuracy and reliability in predicting heat transfer performance. The study concluded that ETSC can operate stably at irradiation intensities exceeding 700 W/m^2.

3.2 Summary

One significant focus in exploring alternative thermal energy storage (TES) materials is investigating Hitec molten salt for TES applications. Hitec molten salt, comprising a blend of lithium, sodium, and potassium nitrate, has garnered significant recognition for its favorable thermophysical attributes. These properties encompass notably high thermal conductivity and specific heat capacity. These inherent characteristics render Hitec molten salt an exceptional choice for thermal energy storage systems deployed in solar power facilities and other renewable energy applications. Moreover, its high stability and long-term heat storage capacity further enhance its suitability as an efficient thermal energy storage material. Various factors influence the phase change behavior of Hitec molten salt. Previous research indicates that the compositional makeup of molten salt is a pivotal factor in dictating its phase transition characteristics. Variations in the proportions of constituent salts comprising the Hitec mixture can lead to shifts in melting and freezing points.

Moreover, impurities within the salt can influence phase change behavior, acting as sites for nucleation during crystallization. Such impurities can diminish the extent of supercooling and subsequently impact the overall efficiency of TES systems employing Hitec molten salt. These considerations are paramount in designing thermal energy storage systems utilizing Hitec molten salt to ensure optimal performance. Furthermore, Hitec molten salt presents several merits for applications in TES, such as:

- **High Energy Density:** Molten salt can store much energy in a relatively small volume.
- **Thermal Stability:** Molten salt maintains a stable temperature, ensuring a consistent energy output.
- **Scalability:** These systems can be scaled up or down based on energy storage requirements.
- **Long Lifespan:** Well-engineered systems possess the capacity for extended operational longevity with nominal maintenance requirements.
- **Environmentally Friendly:** Molten salt is non-toxic and environmentally safe, making it a sustainable choice for energy storage

Besides advantages, One of the major concerns associated with using molten salt in TES systems is the potential for corrosion. Corrosion manifests as a multifaceted process characterized by the degradation of materials owing to chemical or electrochemical reactions with the ambient environment. Molten salt's corrosive propensity arises primarily from its highly aggressive nature and adeptness at instigating reactions with various materials under elevated temperatures. Previous studies have shown that corrosion issues can lead to the degradation of containment materials and the release of harmful substances into the salt, negatively affecting the system's performance and safety. Therefore, understanding and mitigating corrosion issues is crucial for successfully implementing molten salt-based TES systems.

4 Conclusions

Thermal energy storage is pivotal in contemporary renewable energy systems, offering a critical remedy to the intermittent nature of renewable energy sources. By harnessing surplus energy during periods of heightened production and reserving it for subsequent use, thermal energy storage adeptly mitigates energy supply-demand disparities. This approach enhances overall system efficiency and promotes a sustainable and reliable energy supply, aligning with the United Nations Sustainable Development Goals (SDGs).

Extensive research has been conducted on the thermal properties of Hitec molten salt, aiming to harness its potential for TES applications. This review provides an overview of the critical characteristics of Hitec molten salt. The findings underscore its favorable thermal properties, including a high specific heat capacity and exceptional thermal conductivity. These qualities position it as a promising candidate for thermal energy storage systems, effectively addressing the challenges of integrating renewable energy sources. Additionally, Hitec molten salt exhibits low viscosity, facilitating efficient heat transfer during storage and retrieval processes. Its utility as a thermal energy storage medium offers multiple benefits, including impressive thermal stability and minimal vapor pressure. These attributes enhance feasibility and elevate the performance of renewable energy systems, contributing to achieving Sustainable Development Goals 7 and 13.

In summary, Hitec molten salt demonstrates exceptional thermal properties, making it an ideal choice for various TES applications. Its efficient thermal energy storage capacity, remarkable thermal stability, low vapor pressure, and exceptional thermal conductivity make it highly versatile. With an operational temperature range typically between 250°C and 550°C, it can be adapted to different thermal energy storage systems. CSP plants have already utilized Hitec molten salt for TES and electricity generation, showcasing its significant impact on advancing thermal energy storage technologies.

To further progress TES using Hitec molten salt, several avenues for future research and enhancements emerge. Exploring new additives or modified salt compositions could fine-tune its thermal properties, aligning to improve sustainable energy systems (SDG 9). Additionally, developing advanced characterization techniques, such as in-situ spectroscopy or imaging, can provide a deeper understanding of Hitec molten salt's behavior and thermal performance, aiding its optimization for real-world applications. Lastly, conducting long-term stability studies under realistic operating conditions is essential to assess the durability and reliability of Hitec molten salt systems, ensuring their long-term contribution to sustainable energy solutions. These future research directions and potential improvements promise to advance thermal energy storage technologies and significantly contribute to global sustainable development efforts, supporting cleaner and more resilient energy solutions in alignment with the SDG.

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