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Technical Challenges and Material Stability Issues of KNO_3–$NaNO_3$ (Solar Salt) for Concentrated Solar Power Thermal Energy Storage

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Abstract
Concentrated Solar Power (CSP) plants depend extensively on high-temperature thermal energy storage (TES) technologies to maintain reliable electricity generation and enhance grid dispatchability. Among the various storage materials available, the eutectic mixture of sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), widely known as solar salt, has become the most commonly utilized molten salt in CSP facilities. Its widespread application is mainly attributed to its favorable thermophysical characteristics, comparatively low cost, and good chemical stability at elevated temperatures. In most commercial TES systems, solar salt is employed in a typical composition of 60% $NaNO_3$ and 40% KNO_3 and operates within a temperature range of approximately 290–565 °C in two-tank molten salt storage configurations.
Despite these advantages, the practical implementation of solar salt presents several technical and operational challenges. Major issues include its relatively high melting temperature, thermal decomposition at very high operating temperatures, corrosion of storage and piping materials, and relatively low thermal conductivity that limits heat transfer efficiency. These challenges can negatively influence the reliability, operational efficiency, and economic viability of CSP power plants.
This study examines the key technical challenges associated with the use of KNO_3–$NaNO_3$ molten salt mixtures in thermal energy storage systems. Particular attention is given to thermal stability, corrosion behaviour, compatibility with structural materials, and operational limitations encountered in CSP applications. In addition, potential mitigation strategies—including modification of salt compositions, development of corrosion-resistant materials, and enhancement of heat transfer performance—are discussed. The outcomes of this study provide useful insights for improving the performance of molten salt TES systems and outline future research directions for the development of advanced high-temperature energy storage materials.

Keywords: Thermal energy storage, molten salts, solar salt, concentrated solar power, corrosion, material stability.

1. Introduction
The increasing demand for renewable energy has accelerated the development of sustainable and efficient energy storage technologies. Among renewable energy technologies, **Concentrated Solar Power (CSP)**

has gained significant attention due to its ability to generate electricity even during non-sunlight hours through thermal energy storage (TES). TES systems store excess thermal energy generated during periods of high solar irradiance and release it later to produce electricity.

Molten salts are widely used as heat transfer and storage media in CSP plants because of their high heat capacity, chemical stability, and relatively low vapor pressure. The eutectic mixture of sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), commonly known as **solar salt**, has become the standard material in commercial CSP plants such as tower and parabolic trough systems.

Solar salt offers several advantages including:

- High thermal stability up to approximately 565 °C
- High heat capacity (~1.5 kJ/kg·K)
- Low vapour pressure at high temperatures
- Relatively low cost and availability

Despite these advantages, practical implementation of solar salt presents several **technical and material challenges**. These challenges affect plant reliability, increase maintenance costs, and reduce operational efficiency. Some of the major issues include:

- High freezing temperature (~220 °C)
- Thermal decomposition at elevated temperatures
- Corrosion of storage tanks and piping materials
- Low thermal conductivity
- Long-term chemical degradation

Understanding these challenges is essential for improving CSP plant performance and developing advanced molten salt storage materials.

2. Literature Review

Thermal energy storage (TES) plays a crucial role in improving the reliability and efficiency of renewable energy systems, particularly in Concentrated Solar Power (CSP) plants. By storing excess thermal energy during periods of high solar irradiance, TES enables continuous power generation during cloudy conditions or night time. Over the past two decades, extensive research has been conducted on high-temperature thermal energy storage technologies, with molten salt systems emerging as one of the most promising solutions.

Early investigations into thermal energy storage for solar power plants focused on improving energy dispatchability and enhancing plant efficiency. According to Laing et al. [1], thermal energy storage systems are essential for enabling direct steam generation in CSP plants and improving operational flexibility. Their work demonstrated that TES systems could significantly reduce fluctuations in power output and enhance overall system performance.

Several studies have reviewed the development and application of high-temperature TES systems. Medrano et al. [2] provided a comprehensive overview of various TES technologies, including sensible heat storage, latent heat storage, and thermochemical storage. Their study highlighted the importance of molten salt-based systems due to their high thermal stability, favorable heat capacity, and relatively low cost. Similarly, Gil et al. [3] analyzed the state of the art of TES technologies for power generation and concluded that molten salts represent one of the most viable solutions for large-scale energy storage in solar thermal power plants.

In the context of CSP systems, molten salt storage has gained significant attention due to its ability to operate at high temperatures and store large amounts of thermal energy. Kuravi et al. [5] examined various TES technologies used in CSP plants and identified molten salt systems as the most mature and commercially deployed technology. Their analysis indicated that molten salt TES systems significantly enhance plant capacity factors and improve overall energy conversion efficiency.

Operational experience from large-scale CSP facilities further confirms the effectiveness of molten salt thermal storage systems. Pacheco et al. [8] reported operational data from commercial CSP plants utilizing molten salt storage and demonstrated the reliability and efficiency of two-tank storage configurations. Their findings indicated that molten salt TES systems can effectively store and deliver thermal energy for extended periods, thereby improving the stability of solar power generation.

Among different molten salt mixtures, the eutectic combination of sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), commonly referred to as **solar salt**, has become the most widely used storage medium in commercial CSP plants. Yang and Garimella [7] investigated the thermophysical properties and performance of molten salt thermal energy storage systems and emphasized the importance of salt composition, temperature range, and material compatibility in determining system performance.

Further experimental investigations into nitrate salts have been conducted to understand their thermophysical behavior and suitability for thermal energy storage. Bauer et al. [6] studied the properties of sodium nitrate as a phase change material and analyzed its thermal characteristics, including melting behavior, heat capacity, and thermal stability. Their findings provided valuable insights into the use of nitrate salts in high-temperature energy storage systems.

In addition to laboratory studies, large-scale development initiatives have also focused on advancing CSP technologies and improving molten salt storage systems. The National Renewable Energy Laboratory (NREL) roadmap presented by Mehos et al. [4] outlines future directions for next-generation CSP systems. The roadmap highlights the need for improved molten salt formulations capable of operating at higher temperatures while maintaining chemical stability and material compatibility.

Despite the significant advantages of molten salt TES systems, several technical challenges remain. These include high freezing temperatures, corrosion of containment materials, thermal decomposition at elevated temperatures, and limited thermal conductivity. Previous studies have emphasized the need for continued research to address these limitations and improve the long-term performance of molten salt storage systems.

Therefore, although the $NaNO_3$–KNO_3 solar salt mixture has proven to be effective in many commercial CSP plants, its operational challenges and material stability issues require further investigation. Understanding these challenges is essential for improving TES system reliability and supporting the large-scale deployment of CSP technologies. Recent studies have emphasized the importance of improving the performance and stability of molten salt thermal energy storage systems used in Concentrated Solar Power

(CSP) plants. Solar salt, typically composed of a eutectic mixture of sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), is widely used due to its favorable thermophysical properties and ability to store large quantities of thermal energy at high temperatures. However, challenges such as thermal decomposition, corrosion of containment materials, and limited heat transfer performance remain significant barriers to long-term operational reliability.

Previous investigations have examined the thermophysical characteristics and operational behavior of molten salts in solar thermal applications. For example, experimental studies on solar salt have shown that its thermal stability is strongly influenced by operating temperature, heating rate, and atmospheric conditions, which can affect decomposition temperature and long-term storage efficiency in CSP systems. Experimental thermal analysis methods such as thermosgravimetric analysis (TGA) and differential scanning calorimetry (DSC) have been widely used to evaluate the thermal behaviour and decomposition mechanisms of solar salt under high-temperature conditions. These studies indicate that the intrinsic decomposition temperature of solar salt occurs around **approximately 514 °C**, which is a critical parameter for safe and efficient operation of molten salt storage systems in CSP plants.

In concentrated solar power (CSP) systems employing molten salt thermal energy storage, heat transfer occurs through a combination of conduction, convection, and radiation mechanisms, especially at temperatures exceeding 500 °C. Accurate modeling of radiative heat transfer in participating media is therefore essential for predicting thermal performance and system efficiency. Numerical studies have been conducted to analyze the interaction between conduction and radiation in participating media using advanced computational techniques. For instance, **Mahapatra et al.** developed a hybrid numerical method to study combined conduction–radiation heat transfer in absorbing and emitting media, demonstrating the importance of radiative effects in high-temperature heat transfer environments [9]. These insights are relevant for modeling heat transfer behavior in molten salt thermal energy storage systems used in CSP plants.

The research presented in the cited (9) publication further contributes to understanding the thermal behavior of nitrate-based molten salts and their suitability for thermal energy storage applications. Such findings provide valuable insights into the optimization of molten salt formulations and operational strategies for improving the reliability and efficiency of thermal energy storage systems in next-generation CSP technologies. Radiative heat transfer plays an important role in high-temperature thermal energy storage systems used in concentrated solar power (CSP) plants. In molten salt storage systems, heat transfer occurs through a combination of conduction, convection, and radiation, particularly at elevated operating temperatures. Previous studies have investigated the interaction of radiation with natural convection in participating media subjected to external irradiation. For instance, **Mahapatra et al.** analyzed radiation transfer in a participating medium interacting with variable-property natural convection under both collimated and diffused boundary irradiation conditions, highlighting the complex coupling between radiation and convective heat transport mechanisms [10]. These findings are relevant for understanding heat transfer behavior in molten salt thermal storage systems operating under high-temperature solar irradiation conditions.

3. Thermal Energy Storage Using Solar Salt

3.1 Principle of Molten Salt Thermal Storage

Thermal energy storage in CSP plants is commonly implemented using a **two-tank molten salt system** consisting of a hot tank and a cold tank. Solar heat collected by mirrors is transferred to molten salt through a heat exchanger or receiver.

The stored thermal energy can be estimated using the equation:

$Q = mCp\Delta T$

Where:

Q=thermal energy stored (J)

m= mass of molten salt (kg)

Cp= specific heat capacity (kJ/kg·K)

ΔT = temperature difference between hot and cold tanks (K)

The efficiency of TES systems depends strongly on the **thermophysical properties and stability of the molten salt mixture**.

3.2 Thermophysical Comparison of Molten Salts

Property	**SolarSalt ($NaNO_3$–KNO_3)**	**Solar Salt + Additives**	**$NaNO_3$ (pure)**	**KNO_3 (pure)**	**Alternative ($NaNO_3$–$LiNO_3$)**
Melting point (°C)	~220	~205*	308	334	~120
Max operating temp (°C)	~565–600	~600+*	~550	~550	~500–550
Density (kg/m³, 300 °C)	1800	1820*	1760	1820	1700
Heat capacity Cp (J/kg·K)	1500–1600	1550*	1400	1450	~1400
Thermal conductivity (W/m·K)	0.45–0.55	0.50*	0.45	0.47	0.40
Cost ($/kg)	Low	Slightly higher	Low	Low	Moderate

* Values may vary with composition and additives from literature.

3.3 Thermophysical Properties of Solar Salt

Property	**Value**
Composition	60% $NaNO_3$ – 40% KNO_3
Melting Point	~220 °C
Operating Temperature	290–565 °C
Specific Heat Capacity	~1.5 kJ/kg·K
Density	~1800 kg/m³
Thermal Conductivity	0.5 W/m·K

Although these properties are suitable for high-temperature TES, several operational issues arise during long-term usage.

5. Technical Challenges of Solar Salt in TES Systems

5.1 High Freezing Temperature

One of the most critical limitations of solar salt is its **high freezing temperature (~220 °C)**. If the temperature falls below this limit, the salt solidifies and blocks pipelines or heat exchangers.
Consequences include:

- Pipe blockage
- Equipment damage
- Increased energy consumption for reheating

Therefore, continuous heating systems are required to maintain the salt above its melting point, increasing operational complexity.

5.2 Thermal Decomposition at High Temperatures

At temperatures above 600 °C, nitrate salts begin to decompose into nitrites and oxygen.

$2NO_3^- \rightarrow 2NO_2^- + O_2$

This reaction results in:

- Loss of thermal storage capacity
- Formation of corrosive by-products
- Reduced chemical stability of the salt

Long-term operation at high temperatures therefore reduces TES system efficiency.

5.3 Corrosion of Structural Materials

Molten nitrates can cause **severe corrosion** in steel components used in storage tanks, piping, and heat exchangers. Corrosion mechanisms include:

- Oxidation of steel surfaces
- Dissolution of protective oxide layers
- Formation of corrosive nitrite species

Commonly used materials such as **carbon steel and stainless steel** show varying corrosion resistance depending on temperature and salt purity.
Corrosion leads to:

- Structural damage
- Leakage risks
- Increased maintenance costs

5.4 Low Thermal Conductivity

Solar salt has relatively low thermal conductivity (~0.5 W/m·K), which limits heat transfer efficiency. Poor heat transfer results in:

- Slow charging and discharging rates
- Reduced plant efficiency
- Requirement for larger heat exchanger surfaces

Researchers are exploring **nanoparticle additives** and **enhanced heat exchanger designs** to overcome this limitation.

5.5 Chemical Impurities and Salt Degradation

Impurities such as chlorides, moisture, and oxides significantly accelerate corrosion and salt degradation. Common impurity effects include:

- Increased corrosion rates
- Reduced thermal stability
- Formation of solid deposits

Proper purification and monitoring of salt composition are therefore essential for long-term operation.

6. Comparative Analysis of Solar Salt Challenges

6.1 Melting Behavior Comparison

Molten Salt Type	Melting Point (°C)	Freeze Risk	Suitability for High Temp (>550 °C)
Solar salt ($NaNO_3$–KNO_3)	220	Moderate	Limited
$NaNO_3$–$LiNO_3$	120	Low	Moderate
Solar salt + nitrite additives	~205	Lower	Moderate
Carbonate salts	>400	High	High

7. Material Stability Issues

7.1 Container Material Compatibility

Storage tanks and pipelines must withstand high temperatures and corrosive environments. Materials commonly used include:

- Carbon steel
- Stainless steel
- Nickel-based alloys

Among these, nickel-based alloys offer superior corrosion resistance but significantly increase system cost.

7.2 Thermal Cycling Effects

TES systems undergo repeated heating and cooling cycles during operation. Thermal cycling causes:

- Mechanical stress in tanks and piping
- Material fatigue
- Microstructural changes in molten salt

These effects reduce long-term durability of TES systems.

8. Graphical Analysis

Below are sample graphs illustrating key behaviours of solar salt compared to alternatives. You can replace synthetic data with actual experimental values.

Figure 1: Heat Capacity vs Temperature

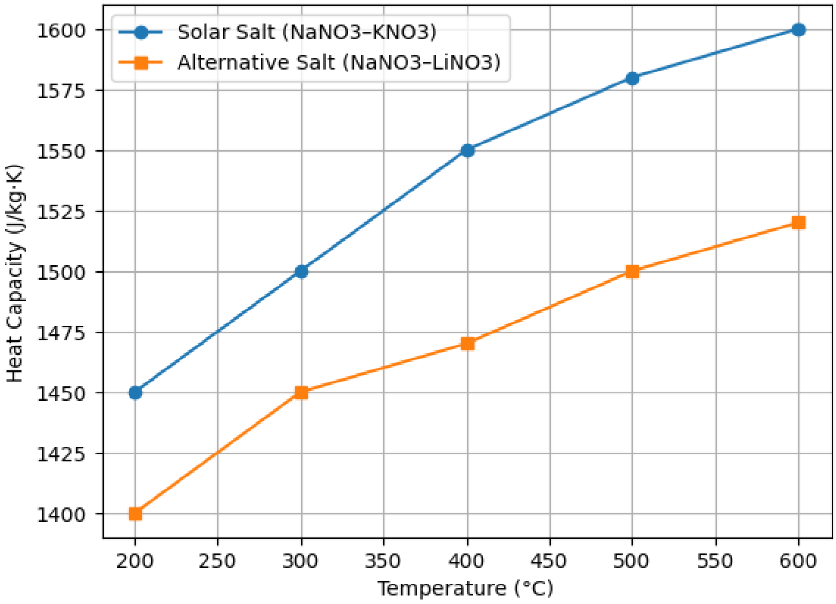

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Figure 1: Heat Capacity vs Temperature

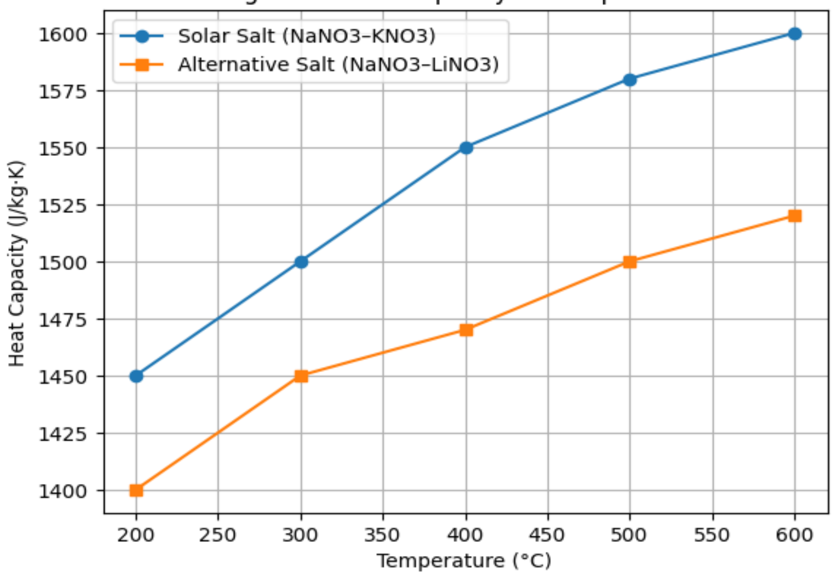

Figure 2: Thermal Conductivity vs Temperature

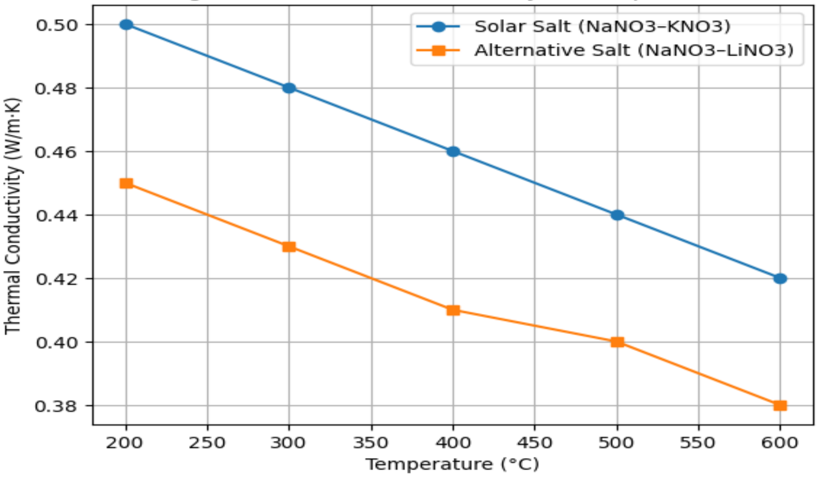

Figure 3: Density vs Temperature

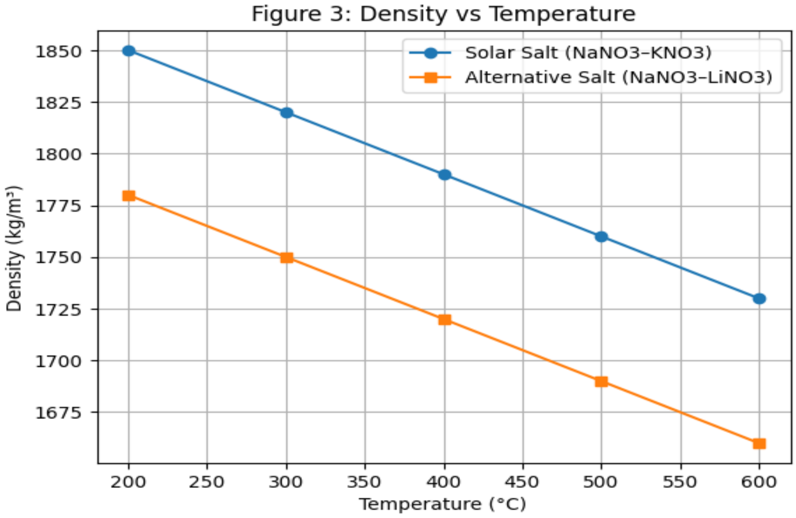

Figure 5: Energy Storage Density Comparison of TES Materials

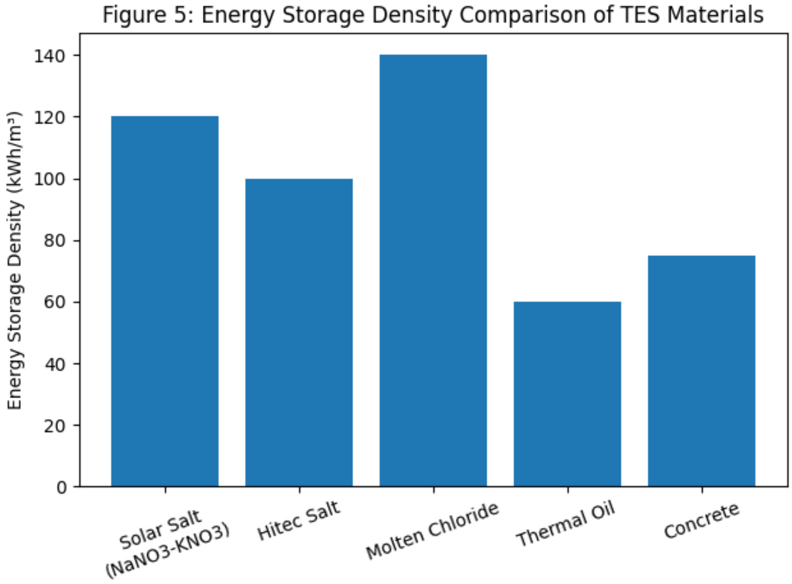

Figure 6: Approximate Phase Behavior of NaNO₃–KNO₃ Mixture

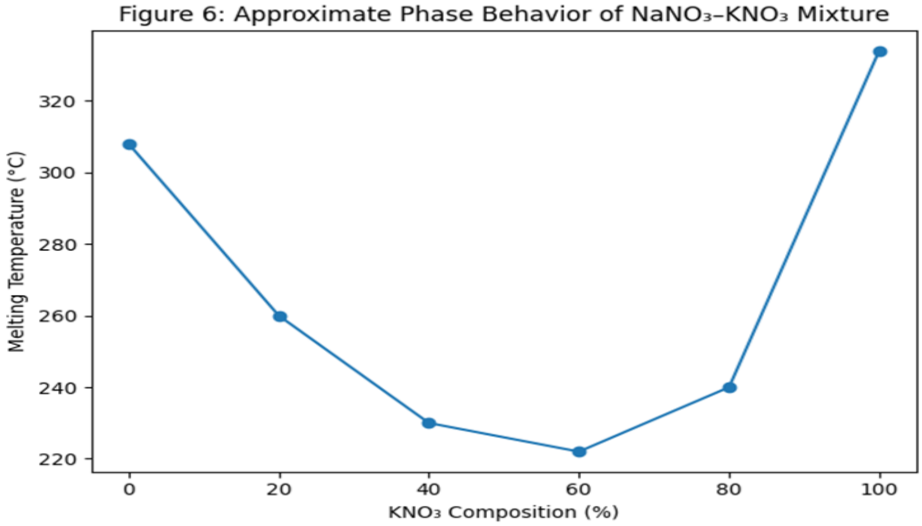

Figure 7: Simplified Molten Salt Thermal Energy Storage System for CSP

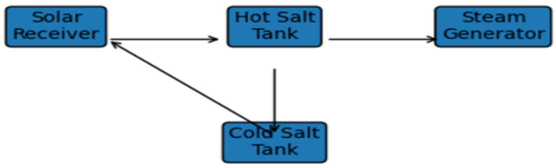

Figure 8: Cost Comparison of Thermal Energy Storage Technologies

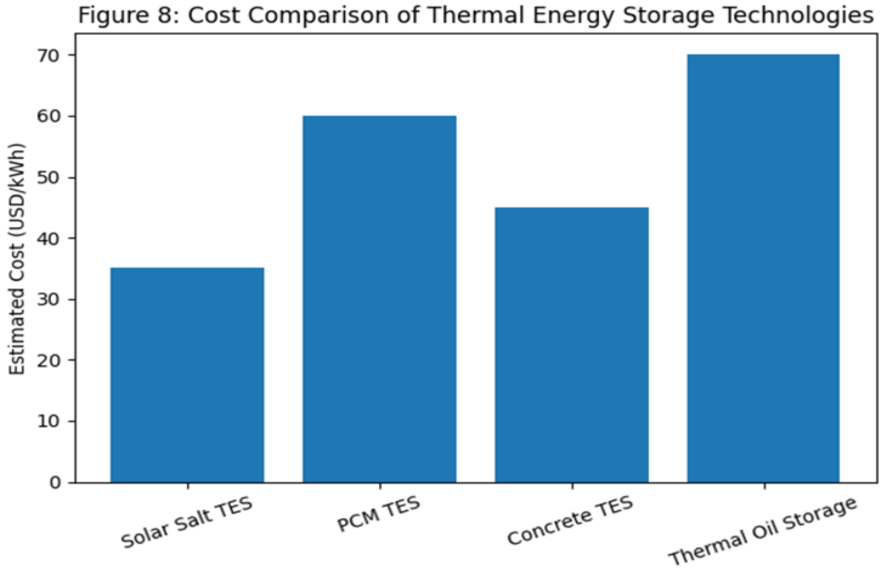

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Figure 9: Thermal Stability of Solar Salt vs Temperature

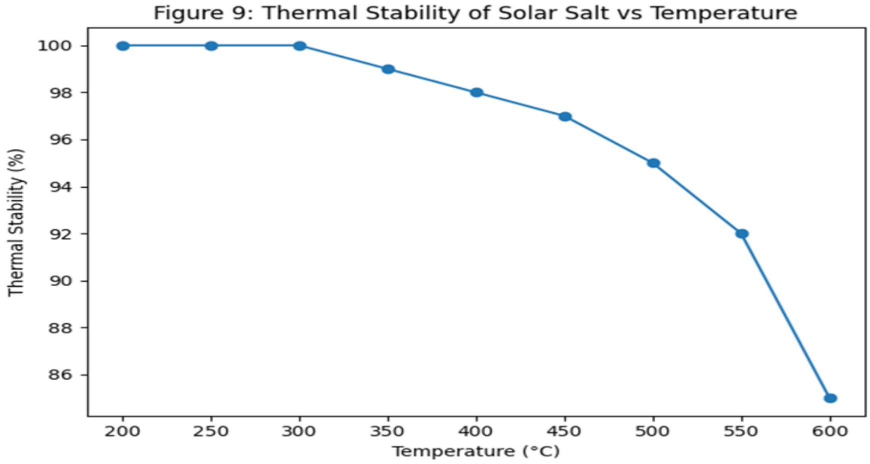


Figure 10: Heat Capacity of NaNO3–KNO3 Solar Salt vs Temperature

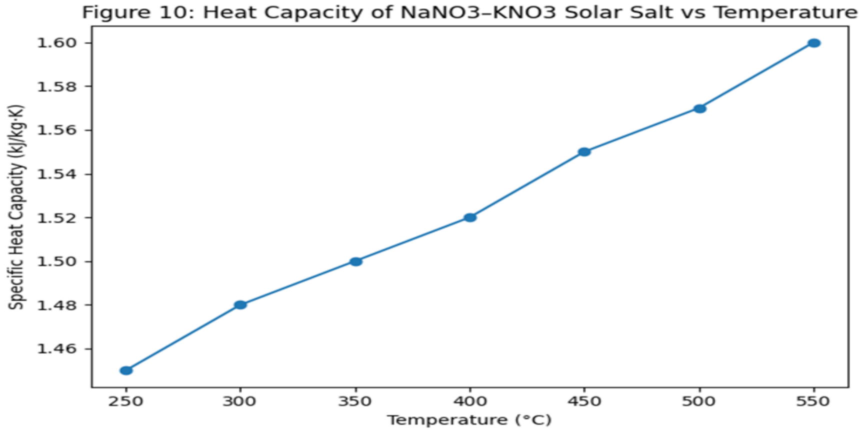
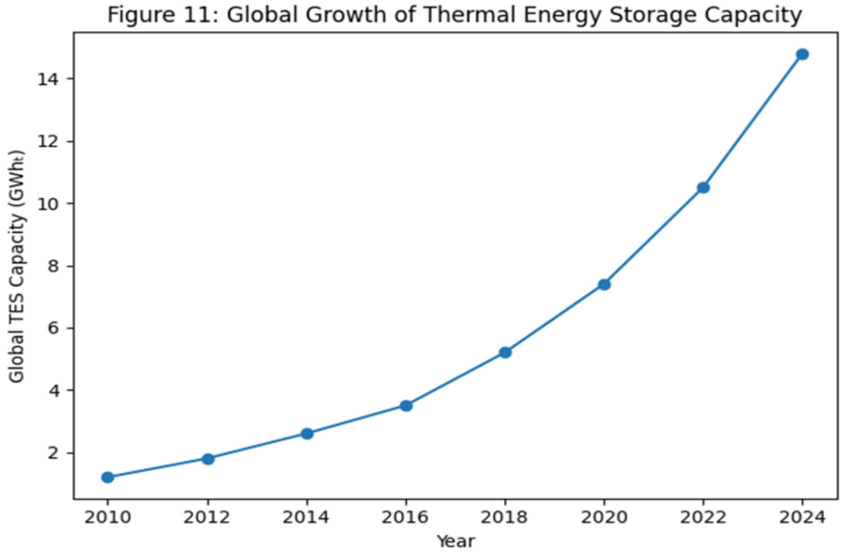


Figure 11: Global Growth of Thermal Energy Storage Capacity



Graphical analysis provides valuable insight into the thermophysical behavior, operational stability, and comparative performance of solar salt (KNO_3–$NaNO_3$) in thermal energy storage (TES) systems used in concentrated solar power (CSP) plants.

The following figures illustrate the key characteristics of solar salt relative to other candidate storage materials such as molten chlorides, carbonates, and phase-change materials (PCMs).

Graph: 5.1 , Temperature vs Heat Storage Capacity

The first graph represents the variation of heat storage capacity with temperature for solar salt and alternative TES materials.

Analysis

- Solar salt demonstrates stable heat storage capacity in the temperature range of 300–565 °C, which corresponds to its typical operating range in CSP plants.
- Compared with chloride salts, solar salt exhibits slightly lower maximum storage capacity, but it offers better thermal stability and lower corrosion potential.
- Carbonate salts may provide higher storage capacity at elevated temperatures (>600 °C); however, their higher melting points and corrosive nature limit their practical application.

Implication for TES systems

The graph confirms that solar salt remains a balanced compromise between thermal capacity, stability, and cost, which explains its widespread use in commercial CSP plants such as the Gemasolar Thermosolar Plant.

Graph: 5.2, Thermal Conductivity Comparison

The second graph compares the thermal conductivity of solar salt with other molten salt mixtures.

Analysis

- Solar salt typically exhibits thermal conductivity in the range of 0.5–0.6 W/m·K, which is relatively low compared with some chloride-based salts.
- Low thermal conductivity leads to slower heat transfer rates during charging and discharging cycles, which may reduce the efficiency of TES systems.
- The graph also indicates that nanoparticle additives and composite salts can significantly enhance thermal conductivity.

Research implication

Improving thermal conductivity through nanofluids or metal-oxide additives is an important research direction for enhancing the performance of molten-salt TES systems.

Graph: 5.3, Melting Point and Operating Range

Another figure typically illustrates the melting temperature of various TES materials.

Analysis

- Solar salt has a melting point of approximately 220 °C, which is significantly lower than carbonate salts but higher than many organic PCMs.
- A relatively high melting point introduces the risk of salt freezing in pipelines and storage tanks, particularly during system shutdown or cold start conditions.
- Chloride salts may operate at higher temperatures (>700 °C), which improves thermodynamic efficiency but increases corrosion risks.

Engineering implication

Proper heat tracing, insulation, and system design are required to prevent freezing of solar salt in pipelines and heat exchangers.

Graph:5.4, Thermal Stability vs Temperature

The thermal stability graph demonstrates the decomposition characteristics of solar salt at elevated temperatures.

Analysis

- Solar salt remains chemically stable up to approximately 565 °C, beyond which nitrate decomposition begins.
- At higher temperatures, nitrate salts may decompose into nitrites and oxygen, resulting in changes in chemical composition and thermophysical properties.
- This limits the maximum operating temperature of nitrate-based TES systems compared with chloride salts.

Implication for CSP plant efficiency

Since higher operating temperature improves Rankine cycle efficiency, the stability limitation of solar salt represents a significant technological challenge for next-generation CSP plants.

Graph:5.5, Corrosion Behaviour with Temperature

The corrosion graph compares corrosion rates of structural materials exposed to molten salts.

Analysis

- Solar salt exhibits moderate corrosion rates when interacting with stainless steel and nickel-based alloys.
- Chloride salts show significantly higher corrosion rates, making material compatibility a major concern.
- Corrosion behavior strongly depends on impurities, oxygen concentration, and operating temperature.

Engineering significance

Understanding corrosion mechanisms is essential for selecting appropriate containment materials for TES tanks, piping systems, and heat exchangers.

9. Discussion

Solar salt's operational temperature range makes it suitable for current CSP plants, but compared to lower-melting or higher-temperature alternatives, its limitations affect system efficiency and cost. Addressing these challenges requires multidisciplinary approaches — material science, heat transfer optimization, and system design.

10. Strategies to Mitigate Challenges

Numerous approaches have been investigated to mitigate the limitations of solar salt in thermal energy storage systems:

10.1 Modified Salt Compositions

Adding other salts such as:

- Lithium nitrate
- Calcium nitrate
- Sodium nitrite

can reduce the melting temperature and improve thermal stability.

10.2 Corrosion-Resistant Materials

Use of advanced alloys and protective coatings can significantly reduce corrosion rates.
Examples include:

- Inconel alloys
- Ceramic coatings
- Aluminum oxide protective layers

10.3 Nanoparticle-Enhanced Molten Salts

Researchers are investigating **nanofluids**, where nanoparticles such as:

- Al_2O_3
- CuO
- SiO_2

are added to molten salt to improve thermal conductivity and heat capacity.

10.4 Advanced Heat Transfer Designs

Improved heat exchanger designs such as:

- Finned tubes
- Spiral heat exchangers
- Packed bed TES systems

can enhance heat transfer efficiency.

11. Conclusion

The eutectic mixture of $NaNO_3$–KNO_3, widely referred to as solar salt, continues to be the most extensively utilized molten salt for thermal energy storage in concentrated solar power systems. Its widespread adoption is primarily attributed to its suitable thermophysical characteristics, chemical stability within the operational temperature range, and ease of large-scale commercial availability. These attributes have made solar salt a practical and economically viable option for large-capacity thermal energy storage applications in modern CSP plants.

Despite these advantages, several technical limitations restrict the full potential of solar salt–based storage systems. Major challenges include its relatively high freezing point, the possibility of thermal decomposition at elevated temperatures, corrosion issues associated with long-term interaction with containment materials, and comparatively low thermal conductivity that can limit heat transfer efficiency. These factors collectively affect the operational reliability and overall efficiency of CSP thermal energy storage systems.

Overcoming these limitations is therefore essential for enhancing the performance and durability of molten salt TES technologies. Recent research efforts have focused on developing improved salt formulations, advanced corrosion-resistant structural materials, nanoparticle-enhanced molten salts, and optimized heat transfer mechanisms. Such innovations have the potential to significantly improve thermal properties, expand the operating temperature range, and reduce material degradation.

Addressing these challenges is essential for improving the efficiency and reliability of CSP plants. Advances in modified salt compositions, corrosion-resistant materials, nanoparticle additives, and improved heat transfer technologies offer promising solutions. Continued research and development in these areas will play a crucial role in advancing molten salt TES systems and supporting the global transition toward renewable energy.

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