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A review of the effects of different parameters on salt-based solar thermal energy storage systems

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Phase change materials (*PCMs*) used for thermal energy storage (*TES*) have shown to be particularly promising, especially in light of the growing need for a wide variety of energy-related applications. This article discusses the usage of packed beds made from phase change materials in solar energy storage devices for variable temperature environments. The primary heating/cooling technologies and associated thermal energy storage difficulties have also been examined from the perspective of engineering applications. The packed bed's history from a thermodynamic perspective, the temperature dispersion inside the packed bed, and several design factors that influence its performance are all covered in the brief description of the packed bed. Energy and exergy efficacy are the foundations of its analysis. The article delves into numerous thermal energy storage methods, with phase change materials being the primary topic and a beneficial means of storing thermal energy. In addition, phase change materials also keep latent thermal energy during phase transitions at almost constant temperatures.

KEYWORDS

thermal energy storage, phase change material (PCM), charging and discharing, heat, sensible

1 Introduction

The best use of solar energy requires a storage facility because of the intermittent supply of solar energy. Various phase-changing materials ($PCMs$) have been evaluated for thermal energy storage (TES) in the realm of temperatures useful for home heating and other applications (Sharma et al., 1990; Liu et al., 2018). Molten salt (MS) is comparably less expensive and has several advantageous physical characteristics suitable for TES applications (Awad et al., 2018; Liu et al., 2018; Raud et al., 2018; Sötz et al., 2020; Calderón-Vásquez et al., 2021; Lee and Jo, 2021; Rong et al., 2021). Solar power is one solution to the global energy crisis, and it also happens to be the cleanest, most sustainable option. Since solar power is inconsistent, the most effective way to harness it is through a solar thermal system coupled with heat storage. The energy storage materials at the heart of a thermal storage system include suitable materials, latent heat materials involving phase shifts, and biological heat

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Abbreviation: DSC, Differential scanning calorimetry; PCM, Phase change material; PBTES, Packed bed thermal energy storage; TES, Thermal Energy Storage; MS, Molten salt; LHTES, Latest Heat Thermal Energy Storage.

storage materials (Cingarapu et al., 2015a; Liu and Yang, 2017; Shere et al., 2019; Sun et al., 2020).

TES, which may be broken down into the three types of sensible heat, hydrothermal heat, and latent heat, is a tested technique for producing reliable renewable energy. When the material changes phases, the latent energy is stored in the *PCM* at aconstant temperature. This method has high efficiency and additional latent heat storage advantages (Huang et al., 2013; Pethurajan et al., 2020). Molten salts (*MS*) are readily available and inexpensive materials that can store huge amount of heat and have the capacity to reach very high energy densities. *MS* storage systems can be sensible or latent. *MSs* are useful for energy storage, however they have significant practical issues (Mamani et al., 2018; Vaka et al., 2020a; Ong et al., 2020; Pan et al., 2020; Wan et al., 2020; Xiong et al., 2021).

The phase change of the *PCM* has an irregular pattern because the melting rate is higher near the fin than farther away. In both pure *PCM* and $PCM - foam$ scenarios, natural convection plays a crucial role in forming the phase interface. When a fin is introduced, the heat conduction helps melt considerably more. When the temperature of the heat source is raised, the total melting time drops dramatically. Compared to melting at 61.0°C, melting at 70°C can be accomplished in 67% less time. Fin-metal foam hybrid has a 63.4% lower total melting time and a 146.44% higher temperature response rate than pure *PCM* (Liu et al., 2022a; Liu et al., 2022b). The *LHTS* system is an important method of energy recovery from waste heat. When the metal foam is utilised in *HTF*, there is a rise in the heat transfer to *PCM*. When metal foam is included in *PCM*, the phase transition isothermal time is increased, and the temperature uniformity of *PCM* is improved. The evaluation choices can serve as scientific design guidelines for enhancing $LHTS's$ thermal storage efficiency (Xiao et al., 2022).

With accurate models for effective thermal conductivity, thermal dispersion coefficient of conductivity, permeability, inertial coefficient, and interstitial heat transfer coefficient, the volume-average method describes the melting and solidification of phase change materials in a graded metal foam. The total melting time of phase change material is reduced by 17.9% in the case of favourable gradient porosity and increased by 35.7% in the case of harmful gradient porosity. Positive gradients significantly impact temperature uniformity, raising it by 10.1%, whereas negative gradients lower it by 16.8%. Both the positive and negative gradients solidify considerably slower than the non-gradient structures5.7% and 38.5%, respectively) (Liu et al., 2022b).

For this reason, phase change materials (*PCMs*), also known as latent heat energy storage materials, are ideal for real-world heat energy applications because they can store and release large amounts of thermal waste energy. Industries as diverse as construction (for heating and cooling) and solar power (for heat production and release), as well as textiles (and even astronautics), have made use of phase change materials (*PCMs*) because of their favourable properties in thermal management (Jo and Banerjee, 2015; Li et al., 2019c; Zhao and Wang, 2019; Vaka et al., 2020b; Shen et al., 2020).

1.1 Basic of thermal energy system (TES)

An overview of the many TES techniques is divided into physical processes, such as sensible and a combination of latent heat and chemical reactions, as shown in Figure 1. Numerous factors must be considered before picking TES content. The most important ones are chemical stability, mechanical toughness, low storage system corrosion density, and high energy storage density Jouhara et al., 2020. Peak load, duty cycle, operating temperature, deeper system integration, and simplicity of control are all things to consider while selecting *TES* material. Furthermore, there are additional requirements for *TES* systems and materials in terms of physical, thermal, economic, finest chemical, the kinetic, ecological, technological, and overall performance (Jouhara et al., 2020).

1.2 Concept of latent heat storage (LHS)

LHS is the term used to describe the heat transfer that results from a phase transition in a particular limited temperature differential range in the suitable material. Different substances, including paraffin wax, ice materials, solar salt, and other nanoparticles combined with *PCMs*, are the most frequently employed (Jouhara et al., 2020). Changes in condensation and evaporation, crystallisation, and melting affect the aggregation state. However, most of the latent phase shifts take place without a distinction in the aggregation state in the solid or liquid form (Jouhara et al., 2020).

The difference in enthalpy (ΔH) between two fluids corresponds to the stored temperature.

$$\Delta Q = \Delta H = m\Delta h \tag{1}$$

According to the literature assessment, the *LHS* systems' energy storage density is greater than that of *SHS* technologies because they use chemical bond alteration in the mass composition of the material (Jouhara et al., 2020).

The latent heat capacity of a substance is described (Jouhara et al., 2020):

$$Q = m.C_p.dT\,(s) + mL + m.C_p.dT \tag{2}$$

Where m is the mass of the PCMs (kg), L is the enthalpy of fusion; dT is the temperature change (Jouhara et al., 2020).

1.3 General equation for energy storage

The storage material must be chosen with consideration given to the TES's operating temperature range, outside of which the material may undergo decomposition or an unfavourable phase change (Cingarapu et al., 2015b; Li et al., 2019b; Li et al., 2019d). The storage materials' temperature-dependent material properties can significantly alter the storage's behaviour, especially when large temperature swings are involved (Li et al., 2018c).

$$\begin{aligned} E = m_p C_p, s\,(T_m - T_{ini}) + m_p C_p, l\,(T_{in} - T_m) \\ + m_{shell} C_p, shell\,(T_{in} - T_{ini}) \end{aligned} \tag{3}$$

where m_p and m_{shell} are the mass of PCM and other materials, respectively. T_m, T_{ini} and T_{in} are the melting point of PCM, the initial temperature and the inlet temperature. C_p, s and C_p, l reflect the respective specific heat capacities of solid PCM and liquid PCM. Where $C_{p,shell}$ stands for the specific heat capacity of other solid

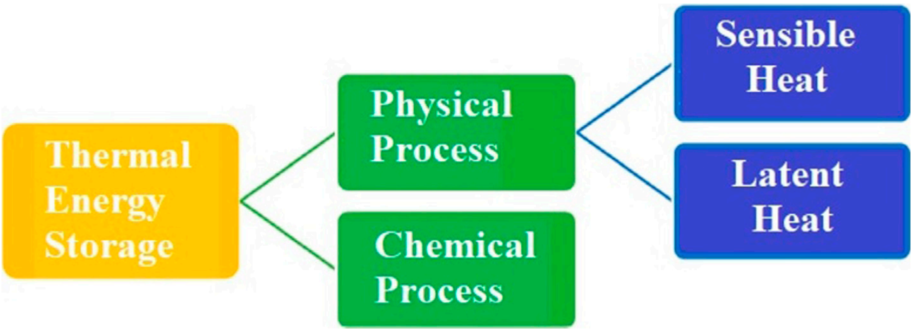

FIGURE 1
Thermal energy storage system (Jouhara et al., 2020).

material. PCM in energy storage systems involves additional crucial equations, as discussed.

$$\left(\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial x}+v\frac{\partial T_f}{\partial y}+w\frac{\partial T_f}{\partial z}\right)=\frac{k}{C_f}\left(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}+\frac{\partial^2 T_f}{\partial y^2}\right)+S_T \tag{4}$$

$$\text{Energy stored: } E_c=\int\frac{C_{p,in+C_{P,out}}\,(T_{in-}T_{out})q_{mdt}}{2} \tag{5}$$

$$\text{Energy released: } E_d=\int\frac{C_{p,in+C_{P,out}}\,(T_{out-}T_{in})q_{mdt}}{2} \tag{6}$$

$$\mathrm{Q}_{\mathrm{charge}}=\cdot m_f\nabla\tau\times\sum\nolimits_{j=1}^{3}\sum\nolimits_{i=1}^{Ncharge}\left(C_{pin}\,T_{in}-C_{pout}\,T_{out}\right) \tag{7}$$

$$\mathrm{Q}_{\mathrm{discharge}}=\cdot m_f\nabla\tau\times\sum\nolimits_{j=1}^{3}\sum\nolimits_{i=1}^{Ncharge}\left(C_{pin}\,T_{in}-C_{pout}\,T_{out}\right) \tag{8}$$

$$P\text{averagre.Charge}=\frac{\mathrm{Q}_{Charge}}{\tau_{Charge}} \tag{9}$$

$$E_c=m_{PCM}\int_{in}^{out}C_{P,PCM}\,dT \tag{10}$$

$$P_{charging}=\cdot m\,C_p\,(T_{in}-T_{out}) \tag{11}$$

$$P_{discharging}=\cdot m\,C_p\,(T_{out}-T_{in}) \tag{12}$$

$$\mathrm{Q}_{inst}=m_sH_f\frac{dF_s}{dt}=-hA\,(T_s-T_O)-\left[\left(mC_{ps}\right)+\left(mC_p\right)m_o\right]\frac{\partial T}{\partial t} \tag{13}$$

Under these conditions, the following equations describe the transient behaviour of a two-dimensional model.

Conservation of mass equation

$$\frac{\partial\left(\epsilon\,\rho_g\right)}{\partial t}+\nabla\left[\rho_g\dot{u}\right]=0 \tag{14}$$

Conservation of momentum equation

$$\frac{\partial\left(\rho_g\dot{U}\right)}{\partial\left(\epsilon\,t\right)}+\frac{\nabla\left[\rho_gU\dot{\dot{U}}\right]}{\varepsilon^2}=\nabla.\left(\frac{U_g}{\varepsilon}\nabla\dot{U}\right)-\nabla P+\rho_g g-\left(\frac{\mu_g}{K}+\frac{C_{F\rho}}{\sqrt{K}}\left|\dot{U}\right|\right)\dot{U}. \tag{15}$$

Where is the U_g air viscosity, C_F is the inertial coefficient, and K is the intrinsic permeabilityof the porous medium

Conservation of energyequation for air

$$\frac{\partial\left(\epsilon\,\rho_gC_{P,g}T_g\right)}{\partial t}+\nabla\left[\rho_gC_{p,g}\dot{U}T_g\right]=\nabla.\left(\Gamma_{g,eff}\nabla T_g\right)+h_v\left(\,(T_P)\right)r-T_g \tag{16}$$

where T_g is the air temperature, $(\,(T_P))r$ is the surface temperature of PCM capsules, $C_{p,g}$ is the specific heat capacity of air, $\Gamma_{g,eff}$ air's effective thermal conductivity and a volumetric interstitial heat transfer coefficient, h_v in the right-hand-side final term account for the heat exchange between the air and the capsules .

Energy conservation equation for PCM capsules

$$\frac{\partial\left(\rho_{P\,h_P}\left(T_p\right)\right)}{\partial t}=\frac{\partial}{\partial\xi}\left(k_p\left(T_p\right)\frac{\partial T_p}{\partial\xi}\right)+\frac{2k\,(T_P)}{\xi}\frac{\partial T_P}{\partial\xi} \tag{17}$$

Where ξ is the radial coordinate inside each capsule, h_p is the enthalpy of PCM, ρ_P and $k_\mathrm{p}$are values for PCM's density and thermal conductivity.

2 Previous experimental investigations on an energy storage system with various salt

Different salts have been used as energy storage in several practical analyses to evaluate solar energy storage's effectiveness. Investigations were conducted on several characteristics, including stability, material performance, characterization, charging and discharging time. Various researchers conducted crucial studies on solar energy storage using salt as storage material, resulting in novel materials being developed. A combination of nanoparticles and salt, the manufacture of materials, and the confirmation of experimental findings with numerical models are studied and evaluated by researchers (Sharma et al., 1990; Zhao and Wu, 2011; Olivares and Edwards, 2013).

The temperature distributions and the heat transfer coefficients were calculated using steam as the *HTF* during the stages of storage and discharge. The operating parameters determined and analyzed were: heat transfer rate, steam flow direction, heat transfer fluid temperature, and initial discharge tank temperature (Mao et al., 2010).

The eutectics of alkali chloride salts were regulated using 1% silica nanoparticles, which resulted in the heat capacity of the

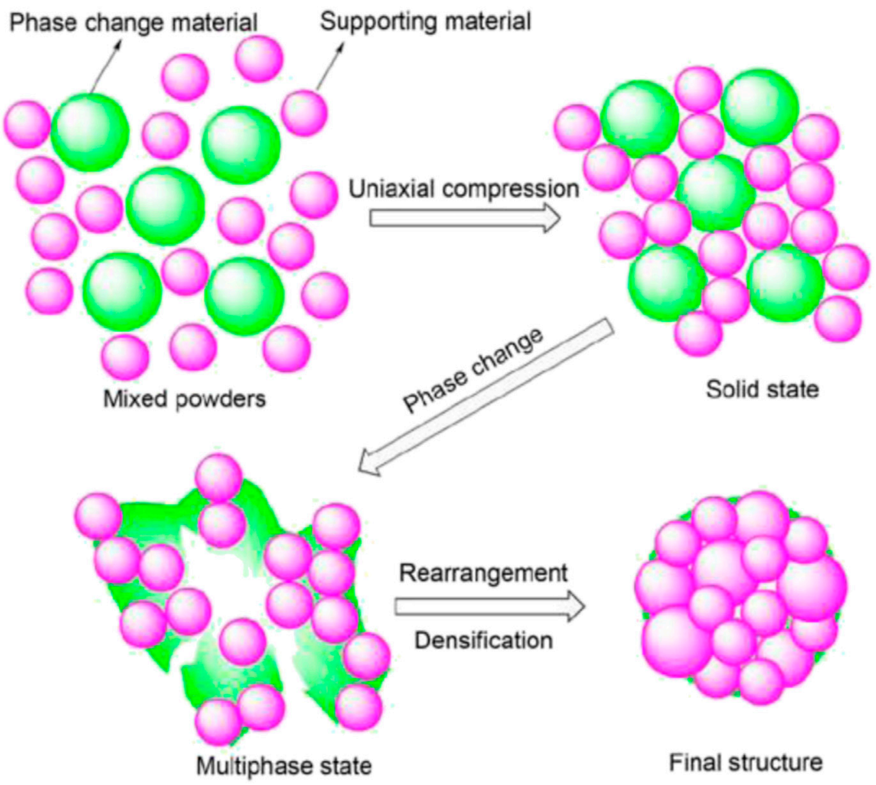

FIGURE 2
Schematic of the mechanism of microstructure development in *PCM* and ceramic Skelton materials (Ge et al., 2014). Licence not required (Creative Commons CC-BY license).

nanofluid increasing by 14.5%. *SEM* was used to examine eutectic nanoparticle dispersion. Three transportation networks are to blame for this unusual behaviour (Shin and Banerjee, 2011). The *PCM* is composed of a eutectic solution of lithium and sodium carbonates. At the same time, magnesium oxide serves as the ceramic's skeleton and carbon nanotubes or graphite flakes as the thermal conductivity enhancer (Ge et al., 2014). The *PCM* and ceramic Skelton materials' microstructure formation process is shown in Figure 2 (Ge et al., 2014).

Researchers have identified and examined two crucial variables that control the storage system. Each significantly impacts reaction kinetics andhe reactor's thermal power (Michel et al., 2014). A schematic and photographic representation of a prototype module is shown in Figure 3 (Michel et al., 2014).

High-temperature heat transmission characteristics of an *MS* thermocline storage tank were investigated experimentally using *MS* as the *HTF* and ceramic particles as the filler metal (Yang et al., 2016). The experimental outputs validate the successful outcomes of the numerical simulation and provide references for engineering design.

An experimentally and numerically generated extremely high-temperature latent *TES* system with spherical capsules is investigated for its dynamical thermal efficiency (Bellan et al., 2015). The experimental configuration of the *TES* system using *MS PCM* capsules is shown in Figure 4 (Bellan et al., 2015).

The eutectic *MS* is used in constructing the *LHTES* as the *PCM* to effectively utilise solar energy at a moderate temperature of roughly 2000°C. By enhancing the $PCM's$ effective thermal conductivity, the nickel foam is added to pure *PCM* to create a composite, which serves as an energy storage material and improves the overall performance of the *LHTES* arrangement. The outcome demonstrates that the thermal conductivity of the *PCM* increases by encasing *MS* in nickel foam, which enhances the performance of the *LHTES* system (Zhang et al., 2016). The lab facilities of the *TES* tank's system is shown in Figure 5 (Zhang et al., 2016).

A modest amount of hydrated salt, which is a *PCM* in *LHTES*, can store a significant amount of energy. The low heat conductivity problem is overcome in the copper foam/hydrated salt composite *PCM* by using modified sodium acetate trihydrate (*SAT*) as the *PCM* and copper foam as the supporting matrix. Changing the *SAT* with artificial substances first resolves the dissociation concerns and the lowering of temperature. Strong thermal conductivity, low upper-cooling, and good thermal stability make it an ideal material for *TES* (Li T. X. et al., 2017).

Thermochemical energy storage compounds of magnesium chloride hydrates show the potential for higher energy storage. With a relative humidity of less than 30%, it has been determined that magnesium chloride hydrates are the sole option (Kohler et al., 2018).

A novel packed bed thermal energy storage (*PBTES*) system by macro-encapsulating *MS* phase transition material at high

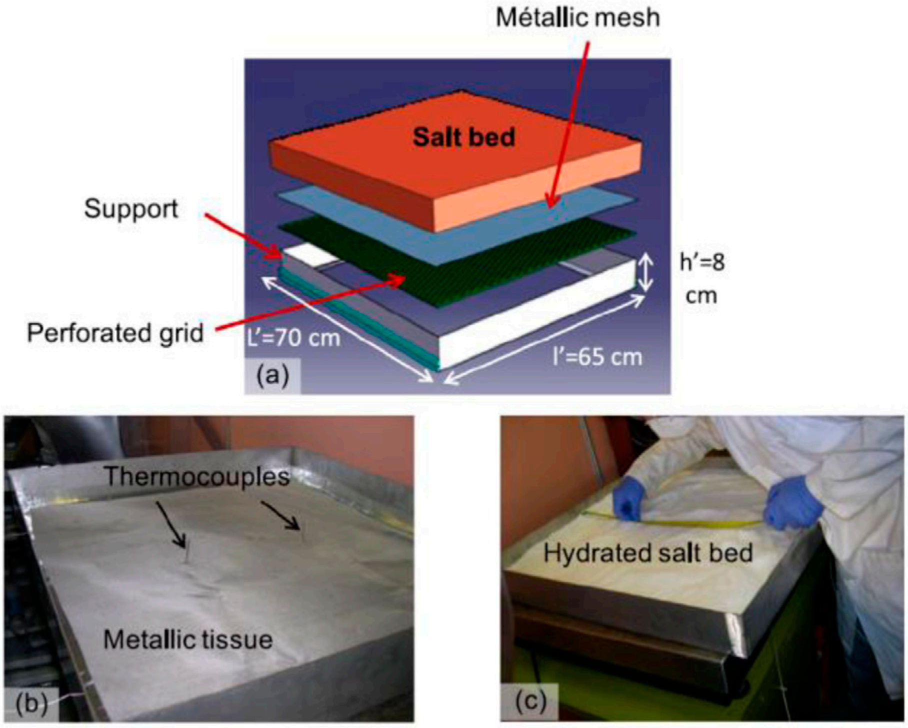

FIGURE 3
Schematic and photographic view of a module of the prototype (Michel et al., 2014). License Number: 5526331096176.

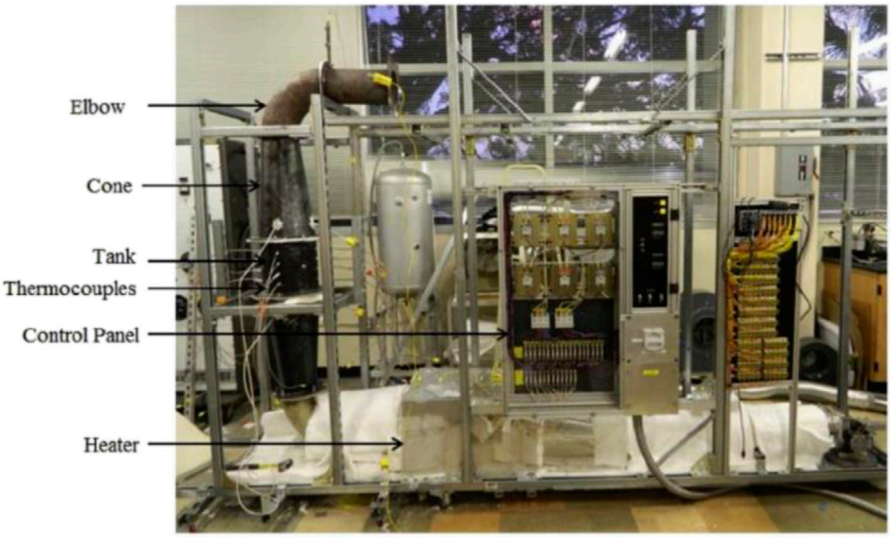

FIGURE 4
Energy storage system laboratory using PCM capsules made of molten salt (Bellan et al., 2015). License Number: 5526331356459.

temperatures is setup to identify the feasibility of the present idea (Li M. J. et al., 2018). Ternary carbonate is the best *PCM* alternative. Additionally, as a first step in utilizing the technology and enhancing thermal performance optimization, the research recommends a design for a PBTES. Both the *PCM* and the packed bed energy storage device are displayedin Figure 6 (Li et al., 2018b).

FIGURE 5
Photographic view of lab facilities of the TES tank (Zhang et al., 2016). License Number: 5526340217542.

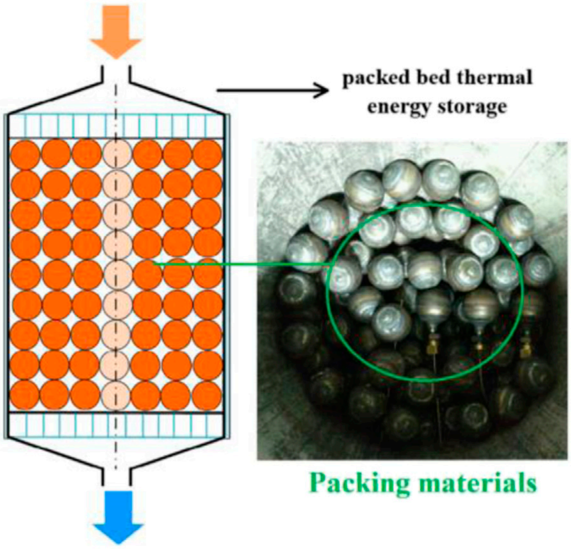

FIGURE 6
Packed bed TES system and PCM (Li et al., 2018c). License Number: 5526340562731.

Utilizing thermal analytic techniques for *TES*, a novel *PCM* was studied as a low-melting-point eutectic salt of an alkali nitrate/nitrite combination (Li et al., 2018b). Regarding the thermal characteristics of the eutectic salt combination, the study found that this innovative multi-component eutectic system might be used as an efficient heat transfer and storage material for low-heat *TES* technologies (Li et al., 2018b).

The thermal system was analyzed experimentally (Li M. J. et al., 2018) to determine the fusion enthalpy change, specific heat, density, and other thermo-physical parameters of the eutectic salt mixture. Figure 7 illustrates the system's latent heat storage and transport principle (Li et al., 2018b).

There is some speculation that *TES* implemented as a single tank, also known as the thermocline form of storage, would be a more cost-effective choice than the *MS* thermal storage system implemented as two tanks (Martin et al., 2018). More cost savings are anticipated in thermocline storage by replacing a sizeable portion of solar salt with a useful cost-filler material. Such filler materials must maintain MS stability at temperatures as high as 560°C. Their study determines whether quartzite and basalt are workable suggestions for thermocline storage employing filler components—solar latent heat storage diagram in Figure 8 (Martin et al., 2018).

The possibility for salt-based *TES*, which may be suitable for high-temperature *TES* in solar power technologies, was discussed By investigators (Wu et al., 2018; Yuan et al., 2018). The *PCM TES* experimental facilities are shown in Figure 9 (Yuan et al., 2018).

Phase change materials (*PCMs*) used as energy storage materials, such as different salts, inorganic salt, *MS*, inorganic hydrate salt, and so on, have been the subject of several experimental studies throughout the years. Many academics have discussed *PCMs* in terms of their storage capacity, chemical makeup, thermal characteristics, and other essential factors. Agarwala and Prabhu (2019), Hu et al. (2019), Li et al. (2019a), Li T. X. et al. (2019), Navarrete et al. (2019), Saranprabhu and Rajan (2019a), Saranprabhu and Rajan (2019b), Wang et al. (2019), Zou et al. (2019), Bonk et al. (2020), Li B. et al. (2020), Li Z. et al. (2020), Wang G. et al. (2020), Wu et al. (2020), Xiao et al. (2020), Zheng et al. (2020), Grosu et al. (2021) and Lu et al. (2021) The preliminary experimental analysis on the *TES* system using various salts as the storage medium is shown in Table.1.

3 Previous numerical analysis on TES with different salt as storage materials

Numerous researchers used a numerical approach to examine various salt *TES* systems' performance, stability, and thermal characteristics. The overall interstitial performance anddischarge efficiency is strongly influenced by filler particle size (Yang and Garimella, 2010) Figure 10 shows a schematic design of the thermocline TES system using an axisymmetric coordinate system under study (Yang and Garimella, 2010).

First and second-law efficiency ideas and first-law efficiency with an outflow temperature condition are utilized to evaluate storage performance (Flueckiger et al., 2013). According to the results, the *PCTES* unit's performance can be enhanced by increasing the *HTF* temperature and inlet mass flow rate. Their research showed that all three modified tubes might improve the *PCM* melting process compared to the plain tube (Tao et al., 2012).

Lower melt flow rates, more excellent length ratios, and higher tank heights all increase cycle productivity. Cycle effectiveness is significantly impacted by filler particle size and container volume [67]. A thorough transient and *2D* mathematical model was constructed to study the energy storage efficacy of an *MS* thermocline *TES* with solar thermal power's packed phase transition bed. The outcomes show that employing a packed phase change bed can significantly enhance efficiency (Lu et al., 2015). The concept for the *MS* thermocline *TES* is shown in Figure 11 (Lu et al., 2015).

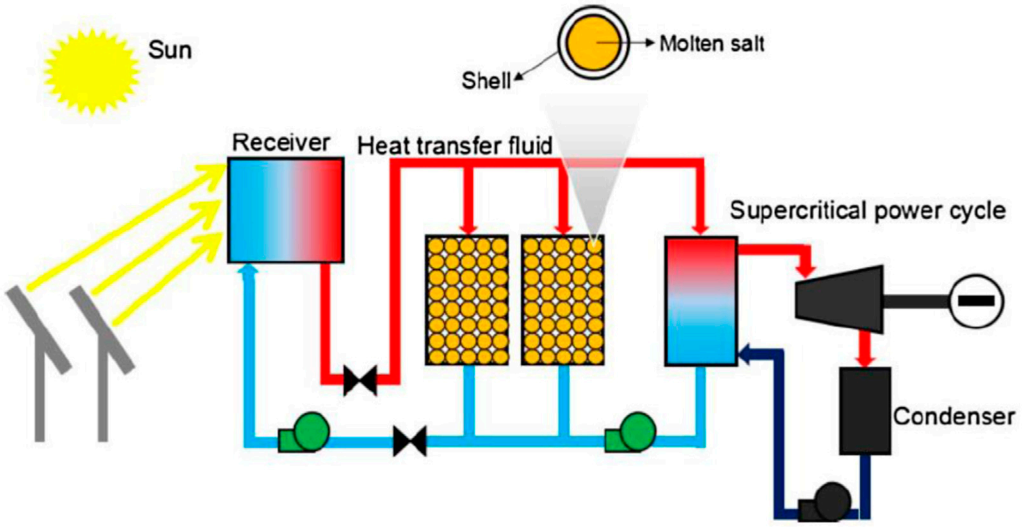

FIGURE 7
Representation of a heat transfer and latent heat storage system (Li et al., 2018b). License Number: 5526340717330.

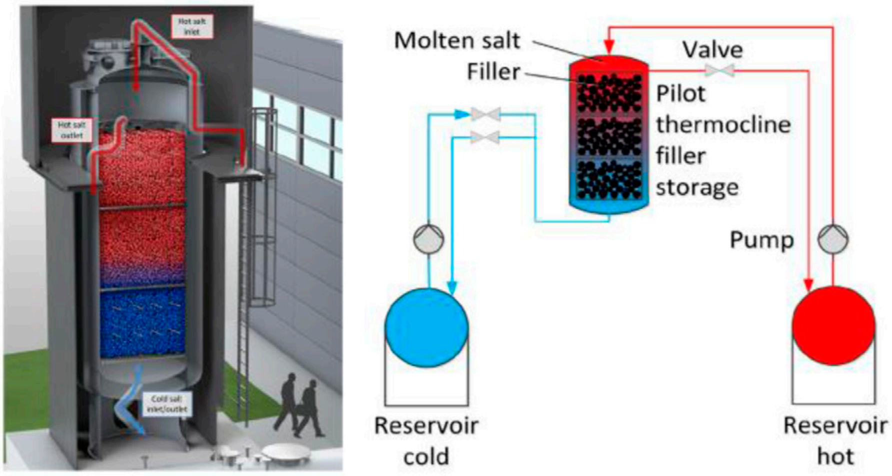

FIGURE 8
Schematic solar latent heat solar storage system (Martin et al., 2018). License Number: 5526341024752.

The importance of using molten salt in high-temperature concentrating solar power (*CSP*) systems as a *HTF* and/or thermal storage medium (Myers et al., 2016). The findings suggested that adding better conductivity nanoparticles, nanoparticles of graphite or metal, could increase the thermal conductivity of *HTFs* (Myers et al., 2016). A nanoparticle-doped ternary eutectic nitrate salt was created to examine how the specific heat is affected. 5–60 nm diameter SiO_2 nanoparticles were tested (Seo and Shin, 2016).

The effect of design and operating parameters on *TES* system effectiveness is examined using thermocline expansion and local fluctuations in salt and filler temperature. Working temperature range affects *TES* performance more than intake salt velocity (Abdulla and Reddy, 2017). The two-tank indirect *TES* system with *MS* is the most popular. The simulation results show that the model can replicate the dynamic characteristics of a two-tank indirect *TES* system with *MS*, including charging and discharging (Li X. et al., 2017).

According to several research studies, salt hydrates may be used in *TES* applications when combined with different nanoparticles. For *TES* applications, several researchers have investigated the chemical and physical properties of *MS* when combined with nanoparticles, tertiary salts, and other salts, including its thermal conductivity, stability, specific heat, and other properties (Du et al., 2017; Jiang et al., 2017). The heat storage and release processes of a molten-salt

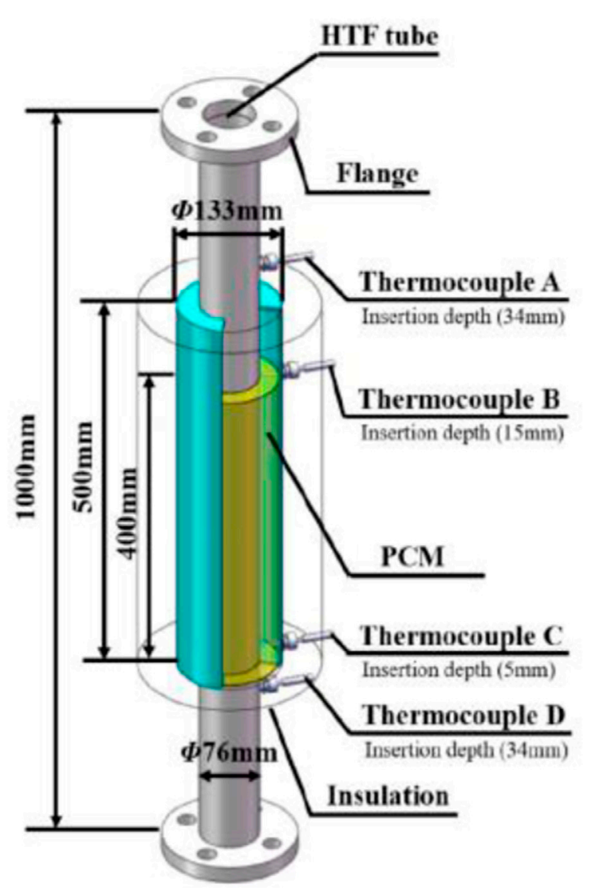

FIGURE 9
Photographic view of the investigational setup of PCM thermal energy storage system (Yuan et al., 2018). License Number: 5526341186605.

thermocline in a porous packed-bed tank are examined using a $2D$ numerical model. Results show thermal gradient layers can continue during heat storage or release (Yin et al., 2017). A multiphase model is created and used for a $3D$ transient CFD examination of the supercooled PCM discharging properties (Zhou and Han, 2017). The potential use of various salt materials, mixing with numerous nanoparticles in TES applications, such as $MgCl_{26}H_2O$, has been revealed by numerous investigations on SEM, TEM, XRD, and other numerical studies (Mamani et al., 2018), $NaKMg–Cl$ (Mohan et al., 2018), molten salt (Niedermeier et al., 2018; Sun et al., 2018; Lappalainen et al., 2019; Gage et al., 2021).

The researchers also suggested that the molten-salt packed-bed TES with thermocline innovation is more expensive because of the integrated design (Zhao et al., 2018a). Deep charging molten-salt packed-bed TES in concentrating solar power plants increases their economic efficiency (Zhao et al., 2018a).

A practical TES arrangement works as a thermal coupler and a heat distributor to balance power and solar heat needs. A hybrid system setup and operation strategy using molten salt to simulate the hybrid system numerically was erected for analysis (Zhao et al., 2018b). It investigated how to input gas temperature, surface gas velocity, and static liquid height affect each other. The numerical results show that the volumetric heat transfer coefficient and the average MS temperature growth rate are both reduced with an increase in the superficial gas velocity or working pressure, while they are improved with an increase in the height of the static liquid (Pu et al., 2019).

As temperatures rise, the radiative heat transfer takes a larger share of the total heat transfer. Deliberation of radiative heat transfer leads to improved temperature transmission between the MS and water. Finally, various scattering and refractive indices' impacts are investigated (Zhu et al., 2019) using CFD (Computational Fluid Dynamics), and the tank's thermal and mechanical properties are quantified. The inflow MS velocity, cold MS temperature, the porosity of the porous bed, diameter, thermal conductivity, and specific heat of the solid filler particle are the factors that affect the tank discharge performance (Wang Y. et al., 2020). As $MgCl_2$ and KCl are already present in the earth, the solar power tower system that uses them requires less MS for thermal storage than the solar salt system (Wang et al., 2021). Using molecular dynamics, we determined the melting point of the binary chloride salts that might be used to store high-temperature energy resources for concentrating solar power. The researchers discovered that the nanoclusters of ions vibrate more intensely, leading to easier crystal fragmentation and a lower melting point. (Zhang and Yan, 2021). The initial numerical analysis of the TES system using salt as the used storage medium is shown in Table 2.

4 Comparative analysis of different properties and parameters of TES

The capacity to store and release substantial amounts of thermal energy at constant temperatures utilising Phase Change Materials ($PCMs$) has garnered much attention. This study aims to evaluate and contrast the efficiency of various $PCMs$ for storing thermal energy (Pereira da Cunha and Eames, 2016). Storage capacity, heat resistance, thermal conductivity, cost-effectiveness, and ecological compatibility are just a few of the factors we'll go over (Kheradmand et al., 2016; Mi et al., 2016; Pereira da Cunha and Eames, 2016; Wang et al., 2016; Meng et al., 2017). Thermophysical properties of some $PCMs$ are shown in Table 3. Table 4 displays the melting point and latent heat of a variety of PCM.

Latent Heat Storage Capacity: The amount of thermal energy stored depends primarily on the $PCMs$ latent heat storage capability. Latent heat measures how much energy may be stored in a given system. One of the most energy-dense $PCMs$ is sodium acetate trihydrate, with a latent heat of 264 kJ/kg.

Thermal Stability: Another crucial aspect to consider is the $PCMs$ thermal stability. Denaturation of the PCM might cause the energy stored in it to be lost and even harm the storage device. Erythritol is a PCM that is highly stable thermally, with a melting point of 121.5°C.

Thermal Conductivity: How efficiently heat is transferred from the PCM to the heat exchanger depends on its thermal conductivity. Paraffin wax and other PCM have poor thermal conductivity and may need reinforcement to facilitate efficient heat transmission.

Cost-effectiveness: The $PCMs$ price plays a significant role in determining whether a thermal energy storage system can be economically viable. Glauber's salt (sodium sulphate decahydrate) is a typical example of a salt hydrate because it meets both affordable and readily available criteria.

TABLE 1 Previous experimental analysis of the TES system with various salt as storage material.

References	Salt	Major findings
Sharma et al. (1990)	Sodium salt hydrates	The investigation revealed that when choosing hydrated salts for TES applications, the activation and optimal criterion ratio is energy and percentage water loss
Awad et al. (2018)	Nano-nitrate MS	The stability and thermo-physical characteristics of materials for storage were examined. When making CuO-nano salt at 450 °C for an hour, they discovered that the one-step process showed a more substantial increase in both latent and sensible heat than the two-step method
Cingarapu et al. (2015a)	Eutectic chloride salt	The results demonstrated that coating coated Zn particles with eutectic chloride salt would increase the TES performance of the system by up to 45% with only 10% vol% particles
Shere et al. (2019)	Inorganic Salts	The study found a 35% increase in thermal conductivity, which can significantly enhance the efficiency of a thermochemical storage medium with an inorganic salt and the heat transfer rate
Huang et al. (2013)	Hydrated salt	According to the examination, the modified $PMMA$ microcapsules' hydrated salt $Na_2HPO_{47}H_2O$ was correctly generated by employing the aqueous copolymerization-solvent volatile process
Zhao and Wu (2011)	Ternary nitrate salt mixture	The characteristics of the tertiary salt mixtures containing $K.NO_3, Li.NO_3,$ and $Ca.(NO_3)_2$ were examined. The researchers concluded that they outperform synthetic oil, which is widely utilised
Fonseca-Aten et al. (2005)	Salt hydrate	According to the research, dehydration and melting together substantially impact salt hydrate breakdown's equilibrium state and heat kinetics. This is crucial for the operation and development of thermochemical storage technologies
Mao et al. (2010)	MS	The HTF input temperature and velocity rate affected heat storage efficiency, especially with a shell-and-tube exchanger
Shin and Banerjee (2011)	Alkali chloride salt eutectics	The investigation revealed that the silicon oxide-based particles increased the specific heat capacity by 14.5% compared to the typical chloride salt eutectic. Three thermal transport pathways also explain the sudden increase in the specific heat capacity
Ge et al. (2014)	Carbonate-salt	The investigation findings demonstrated the effectiveness of synthetic TES structures based on inorganic salts at moderate and high temperatures. The high salt moisture content on ceramic materials increases the strength of the composite structure. However, the low salt wettability of the carbon components causes the composite structure to inflate
Yang et al. (2016)	Molten salt	The research revealed that the temperature profile's slope changed as distance or charging time grew, indicating that the thermocline's thickness had risen
		The affordable filler material can also be utilised to replace expensive MS in thermal storage estimates and MS fluid piston movement
Bellan et al. (2015)	MS	Natural convection made the charging process faster than the discharge mode; when flow velocity or Stefan number increased, $LHTS$ and $SHTS$ decreased, and the container's overall charge/discharge period shortened
Zhang et al. (2016)	Molten-salt	The results revealed that natural convection made the charging process faster than the discharge mode; whenever the flow velocity or the Stefan number is increased, the $LHTS$ and $SHTS$ decrease and the container's total charge/discharge period shortens
Li et al. (2017a)	Copper foam/hydrated salt	Copper foams and SAT hybrid PCM were used to measure the thermal efficiency of a minimal heat storage facility. According to the research, the charging process lasts about 11 min, while the draining process lasts about 10 min
Kohler et al. (2018)	Salt hydrate	The findings indicate that the only drawback to their employment is the relative humidity deliquescence of some salt hydrates is much greater than that of magnesium chloride
Martin et al. (2018)	Molten-salt	The chemical compositions of basalt variants were substantially more complex but also realistic in terms of MS interactions with siliceous oxides. As solar salt shows, both values decrease over time regardless of the filler material
Wu et al. (2018)	MS	The relative humidity deliquescence of some salt hydrates is much greater than that of magnesium chloride
Yuan et al. (2018)	Molten salt	The charging/discharging rates and charge efficiency might be increased more successfully by achieving the temperature difference and fluid velocity. Regarding fluid velocity, as fluid mass increases, the rate of heat storage rises by 28.4%
Hu et al. (2019)	Nitrate eutectic salt with silicon nanoparticles	According to the findings, adding 10 nm SiO_2 nanoparticles to the storage system at an ideal concentration of 1.0 wt% leads to an 8.4% improvement
Navarrete et al. (2019)	Molten salt	The thermal decrement was eliminated by using solid content design, and at 10% PCM for an operating range of temperature of 50°C around the melting temperature, it was possible to store the maximum amount of energy: 10.6 per cent at constant mass and 17.8 percent at constant volume

(Continued on following page)

TABLE 1 (***Continued***) **Previous experimental analysis of the TES system with various salt as storage material.**

References	Salt	Major findings
Saranprabhu and Rajan (2019a)	Solar salt	MgO nanoparticles increased the solar salt's solid phase specific heat and solid phase heat capacity. All MgO-based solar salt composites have better thermal and specific conductivities than pure sun salt
Li et al. (2020b)	Solar salt	The outcomes showed that the SiO_2 nanoparticle greatly improved solar salt's thermal diffusivity and specific heat capacity
Xiao et al. (2020)	Salt/copper foam/nanoparticles	The $LTES$ unit showed, according to the results, how copper foam and Al_2O_3 nanopowder can improve the heat conduction of pure $HITEC$ salt
Grosu et al. (2021)	Molten carbonate salts	The study found that mechanical redistribution of nanoparticles is conceivable, and the associated recovery of the heat capacity improvement was achieved, consistent with previous reports on molten nitrates-based nanofluids
Lu et al. (2021)	Molten salt	The results showed that, with a mass percent concentration of 1 weight percent and an ideal size of 20 nm, the enhancement could reach 10.6% for specific heat capacity, significantly higher than that predicted by classical mixing theory
Olivares (2012)	Molten nitrite/nitrates salt	Results showed that these types of salt had perfect thermal stability from a temperature point of view. The analysis involved testing the characteristics and consistency of molten nitrite/nitrates salt-based energy storage system (up to 700°C)
Liu et al. (2019)	Inorganic hydrated salt	The study's thermal cycle test, heating test, and TGA results showed that the embedding of hydrated salt prevented its rapid dehydration. The microcapsules that were created have excellent thermal stability and dependability

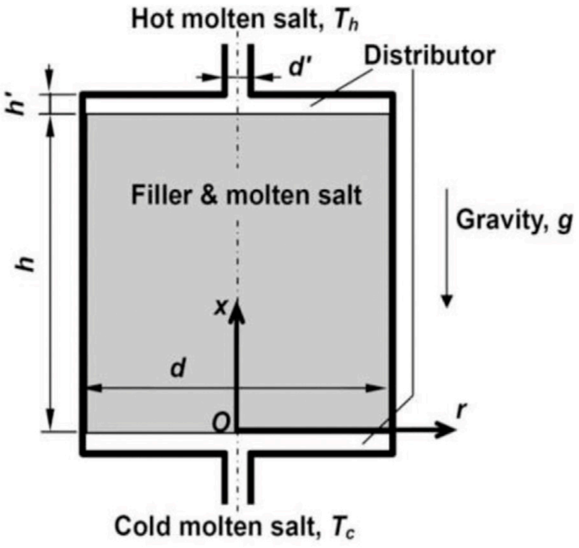

FIGURE 10
Diagrammatic representation of the thermocline TES system (Yang and Garimella, 2010). License Number: 5526341331974.

Compatibility with Environment: When deciding on a thermal energy storage system, it is essential to consider the $PCMs$ low environmental impact. Some $PCMs$, like vegetable oils, biodegrade easily, while others, like mercury, may have harmful effects on the environment.

In conclusion, PCM technology is a workable option for thermal energy storage, although the optimal PCM for a given application will vary depending on its intended use. When choosing a PCM, it is essential to consider its latent heat storage capacity, thermal stability, thermal conductivity, cost, and environmental friendliness.

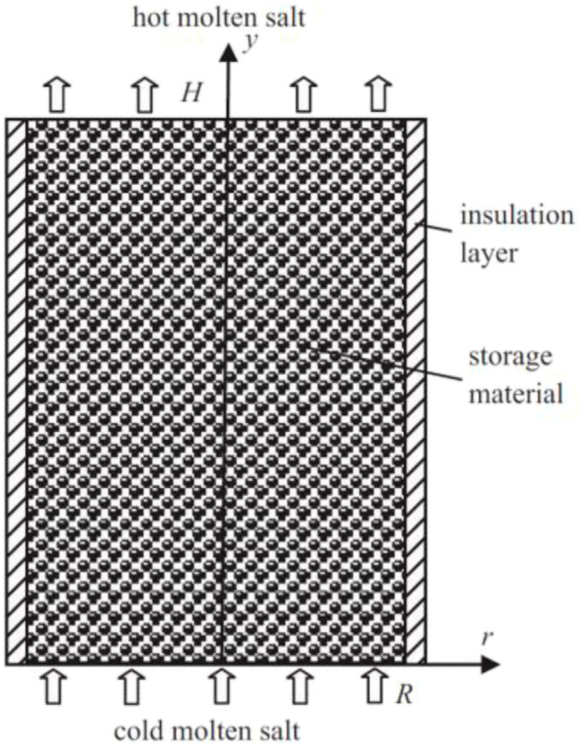

FIGURE 11
Schematic of molten salt thermocline TES (Lu et al., 2015). License Number: 5526341492967.

5 Comparative analysis on *TES* with salt as energy storage material

Different salts utilised in TES systems as energy storage components were the subject of research. Therefore, advancement is

TABLE 2 Previous numerical analysis on *TES* system with salt as used storage medium.

References	Salt	Major findings
Yang and Garimella (2010)	MS	Tank height has a positive effect, but flow velocity has a negative one. Increases in discharge efficiency have been observed when using small filler particles
Flueckiger et al. (2013)	MS	Using the required outflow temperature, the tank's efficiency is assessed in molten-salt energy, exergy, and energy elements. The heat-exchange zones in thermocline containers for small grains are smaller than those in tanks for large granules
Tao et al. (2012)	MS	By using an enhanced tube rather than a plain tube, the *PCTES* unit's total efficiency may be noticeably increased
Yang and Garimella (2013)	Molten-salt	The cyclic behaviour of thermocline *TES* systems is studied using a two-temperature model with *MS* as the *HTF* and low-cost quartzite rock as the filler
Myers et al. (2016)	Nitrate salts doped with CuO nanoparticles	The diffusivity and conductivity of nitrate salts are significantly enhanced by adding 2.0% by vol *CuO* nanoparticles
Seo and Shin (2016)	Salt eutectic	According to the findings, the combination's specific heat increased by 13%–16%, and there was no discernible change in the specific heat concerning nanoparticle size
Abdulla and Reddy (2017)	MS	According to the findings, the operational temperature range appears to have a more significant influence on the effectiveness of the *TES* system than intake salt velocity
Du et al. (2017)	Eutectic chloride salt	According to the analysis, the eutectic mixture's melting point and fusion enthalpy barely changed below 650°C
		High-temperature TES applications up to 650°C might be produced using the ternary eutectic chloride type salt
Jiang et al. (2017)	Eutectic salt	The eutectic salt ($Na_2CO_3 - Li_2CO_3$) exhibits good thermal properties and stability; as a result, the salt act as an effective *PCM* for storing energy at high-range temperatures
Al-Abbasi et al. (2017)	Salt hydrates	The results reflected that cupric sulphate performs with the highest level of efficiency
Yin et al. (2017)	Molten-salt	The construction of the energy storage medium determines the adequate heat storage capacity, which is independent of the operating strategy or the conditions surrounding heat storage
Zhou and Han (2017)	Salt hydrate	Three stages can be used to study the properties of a supercooled *PCM* discharge: steady supercooling, crystallisation, and consistent solidification
Mohan et al. (2018)	Ternary eutectic chloride salt	The most promising alternative, they discovered, was the ternary $NaCl - KCl - MgCl_2$ eutectic and the ideal salt choice for the high-range temperature *CSP* application depended on how sensitive the system was to melting temperature and cost
Niedermeier et al. (2018)	Molten sodium/MSs	A low tank diameter-to-height ratio is also preferred for *MSs*. High porosities, in contrast to sodium, are advantageous since the salts have a lower conductivity than the filler material
Zhao et al. (2018b)	Molten-salt	For packed-bed *TES* systems, the capacity factor improves as the charging cut-off temperature rises and the discharging cut-off temperature falls
Pu et al. (2019)	MS	The results exhibited that the average *MS* temperature increases over time and happens more quickly as the surface gas velocity or operating pressure rises
Zhu et al. (2019)	MS	The temperature on the *MS* side was lower when radiative heat transfer was taken into account than when it was not, even if the tendency is the opposite on the waterside, according to the observations
Wang et al. (2021)	Eutectic salt	The unique eutectic salt of $MgCl_2 - KCl$ offers no advantages when the working temperature is less than 565°C, leading to worse system performance and lower specific work than the common solar salt
Zhang and Yan (2021)	Chloride salt	For solar energy concentration and waste heat recovery, chloride salt eutectics are a viable energy storage material and heat transfer medium
Balasubramanian et al. (2010)	Salt hydrates	Process efficiency might be increased by lowering the heat flow and considering components with superior thermochemical desorption rates, higher specific heat capacities, and lower thermal conductivities

necessary for the thermal performance of *TES* systems. They explored various thermal, physical, and chemical qualities, stability, mixing with nanoparticles, varied concentrations, particle diameter, tank sizes, and packed bed layouts. This section has compared and reviewed a few essential earlier investigations on *PCM* utilised in *TES* systems by different researchers (Jo and Banerjee, 2015). compares the heat capacities of nanomaterials and pure salt mixture for solvents with various chemical compositions; according to the research, there was also a greater prevalence at both ends of the nanoparticles' rise in heat capacity in the solid phase (Zhang et al., 2016). contrasts the *TES* tank's effectiveness for several mass flow rates. Due to variances in stored and released energy, *TES* tank efficiency was close to 71.9%. Neither the *PCMs* thermal performance nor the heat transfer fluid's mass flow rate affected efficiency.

TABLE 3 Thermophysical characteristics of a few PCMs.

Author(s)	Salt-based PCM	Mass ratio	T_m	ρ	L	C_p	λ
			°C	kg/m^3	kJ/kg	J/(kg·K)	W/(m·K)
Pereira da Cunha and Eames (2016)	KNO_3-$LiNO_3$-$NaNO_3$	52:30:18	123.0	2068	140.0	1440.0	0.530
Pereira da Cunha and Eames (2016)	$LiNO_3$-KNO_3	34:66.0	133.0	2018	150.0	1350.0	0.520
Pereira da Cunha and Eames (2016)	KNO_3-$NaNO_2$	56:44.0	141.0	1994	97.00	1740.0	0.570
Pereira da Cunha and Eames (2016)	KNO_3-$NaNO_3$-$NaNO_2$	53:6:41	142.0	2006	110.0	1730.0	0.570
Pereira da Cunha and Eames (2016)	KNO_2-$NaNO_3$	48:52.0	149.0	2080	124.0	1630.0	0.520
Pereira da Cunha and Eames (2016)	$LiNO_3$-$NaNO_2$	62:38.0	15.06	2,296	233.0	1910.0	0.660
Pereira da Cunha and Eames (2016)	$LiNO_3$-$NaNO_3$-KCL	45:50:5	160	2,297	266.0	1690	0.590
Pereira da Cunha and Eames (2016)	$LiNO_3$-KCl	58:42	160	2,196	272.0	1350	0.590
Pereira da Cunha and Eames (2016)	HDPE	---	130	952	255.0	2,150	0.440

TABLE 4 Displays the melting point and latent heat of a variety of *PCM*

Authors and references	PCM	Melting temperature (°C)	Latent heat (kJ/kg)
Kheradmand et al. (2016)	RT10	10.0	150.0
Kheradmand et al. (2016)	MC24	24.0	162.4
Kheradmand et al. (2016)	BSF26	26.0	110.0
Kheradmand et al. (2016)	MC28	28.0	170.1
Meng et al. (2017)	SP29	28.0–30.0	190.0
Meng et al. (2017)	RT18	17.0–19.0	225.0
Mi et al. (2016)	PCM27	27.0	–
Wang et al. (2016)	GH-20	20.0–25.40	33.25

The ability to store heat at various temperature variations of the *PCM* heat storage unit made of copper foam/*SAT* composite and conventional water tanks are compared. Copper foam/*SAT* hybrid *PCM* volume density has a higher latent and sensible heat storage capacity than a water tank (Li T. X. et al., 2017). Li M. J. et al. (2018) discussed the central axis of the packed bed dissimilarity trends of *MS* inside many capsules of varying sizes. It is easy to see that a diameter of 15 mm (0.59 in) charges in 33 min while a diameter of 40 mm (1.57 in) charges in 72.5 min. It has been demonstrated that a *PCM* capsule with a tiny diameter can reduce charging time in half. The exact heat capacity of the salt-containing nanoparticles was higher than that of the essential salt at low concentrations (up to 1.0wt%). However, the specific heat capacity decreases proportionally as more nanoparticles (1.5wt% and higher) are added (Abdulla and Reddy, 2017; Hu et al., 2019) discussed the efficiency of discharging from an *MS* with various filler sizes compared to the inlet velocity. They observed that the maximum discharging efficiency is d = 0.02 m filler size compared to d = 0.04 m. For the *MS*/zirconium ball, *MS*/*SiC* foam heat storage, and thermocline heat storage with pure *MS*, also discussed the effects of various energy storage approaches on heat storage/release performance and outlet temperature fluctuation.

6 Applications of TES

- Heating and cooling buildings: Through thermal energy storage, extra daytime heat can be stored and then released to assist with nighttime heating needs. In a similar vein, thermal energy storage can be used to store nighttime cold air and release it throughout the day to help with cooling buildings.
- Solar power plants: *TES* system allows solar power plants to store excess energy produced during the day and used to create electricity later in the day or at night.
- Industrial processes: Heat created in industrial processes can be stored in *TES* and released as needed to keep temperatures stable.
- Transportation: Electric vehicles can employ *TES* to hold the energy they make when they brake and then release it when needed to keep the vehicle moving.
- Agriculture: Greenhouses can use *TES* to keep plants at a consistent temperature by absorbing excess heat during the day and releasing it at night.

7 Conclusion

The current paper offers a thorough analysis of the literature on the effects of different salts on performance, stability, and other elements employed as PCM materials in TES by numerous researchers. Molten alkali nitrates mainly mix potassium and sodium nitrate with various additives and have occasionally been used as fluids for storing energy or transferring heat. These are the inferences:

- The HTF affected the stability, charging and discharging times, fluid inlet temperature range, flow velocities, salt type, whether it was coupled with nanoparticles, and other essential aspects.
- A densely packed phase transition bed stores latent heat in the MS thermocline TES system. It is the phase change substance that causes the thermocline to shift. As the melting point and phase change material composition increase, so does the suitable discharge energy and efficiency.
- The phase change material's melting point must be between the effective outlet and starting temperatures for optimum thermal storage performance. The high content and latent heat of phase transition materials may also benefit the thermal storage system.
- To assess the effectiveness of the $LHTES$ system, the mean power and energy efficiency are evaluated. The system's overall energy effectiveness remained stable at 72%. Since the charging times for pure MS and composite PCM were similar, the mean powers of the various $PCMs'$ charging procedures showed little change.
- The $HTFs$ mass flow rate affected the discharging procedures' average powers. The average power is higher as the mass flow rate increases. By having better effective thermal conductivity than pure MS, the hybrid PCM system could operate more efficiently overall and produce higher mean power.
- The $MS's$ heat resistance increases as the capsules' diameter rises, which results in longer charging and melting times. It should be emphasized that the reduced diameter of each capsule would result in higher production costs.

Experiments with thermal energy storage involve the controlled release of previously stored heat energy. High heat capacity materials, phase transition materials, and sensible heat storage systems are just a few options for storing thermal energy. Phase change materials are frequently used because of their ability to absorb or release vast amounts of heat energy during their phase transitions from solid to liquid or liquid to gas. Overall, the thermal energy storage experiments aim to increase the efficiency and efficacy of storing and utilizing heat energy, which has important implications in renewable energy systems and lowering conventional energy consumption.

Author contributions

Conceptualization, AK, RM, TA, NG, and AD; methodology, AK, RM, and SS, Software, AK, RM, and SS, Resources, TA, NG, and AD, writing—original draft preparation, AK, RM, SS, and AD writing—review and editing, TA, NG, and AD; visualization AK, RM, and SS, Supervision, AK and TA.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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