Results in Engineering 26 (2025) 104899

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Enhancing thermal energy storage efficiency: Synthesis and analysis of hybrid Nano-PCMs

Jayaprakash V[a,*], Ganesan S[a], Beemkumar N[b], Sunil Kumar M[b], Kamakshi Priya K[c], Nandagopal Kaliappan[d,e,*]

[a] School of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, 600119, India
[b] Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Bengaluru, Karnataka, , 562112, India
[c] Department of Physics, Saveetha School of Engineering, SIMATS, Saveetha University, Chennai, Tamil Nadu, India
[d] Department of Mechanical Engineering, Haramaya University, Harar, Ethiopia
[e] Department of Food Technology, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamil Nadu, India.

ARTICLE INFO

Keywords:
Phase Change Material (PCM)
Heat Transfer
Cascaded TES System
Nano-additives
Thermophysical Properties

ABSTRACT

Heating, processing, and drying operations require substantial heat energy across various temperature ranges, necessitating efficient thermal energy storage solutions. Phase change materials (PCMs) are widely used for this purpose, but their low thermal conductivity limits performance. This study enhances the thermo-physical properties of erythritol and xylitol by incorporating copper (Cu), aluminum (Al), and zinc (Zn) nanoparticles at a 1.5 % weight ratio. The synthesized hybrid nano-PCMs were characterized for thermal properties and assessed in a multi-temperature thermal energy storage system using Therminol-66 as the heat transfer fluid. Results showed significant improvements in thermal conductivity, diffusivity, density, and specific heat capacity due to nanoparticle doping. Among the tested materials, Er-Zn and Xy-Zn exhibited the highest thermal conductivities (0.3012 $Wm^{-1}K^{-1}$ and 0.4496 $Wm^{-1}K^{-1}$, respectively) and achieved superior heat transfer rates (3596.73 KJ and 2629.54 KJ). These findings demonstrate the potential of hybrid nano-PCMs to enhance the efficiency of thermal energy storage systems, making them viable for advanced energy storage applications. Future research should focus on scaling production, long-term stability, and broader application possibilities.

1. Introduction

Thermal conductivity is a key thermophysical property in thermal energy storage (TES) systems, playing a vital role in heat transfer processes within materials. TES applications primarily utilize phase change materials (PCMs), which can be organic, inorganic, or eutectic [1]. PCMs are widely employed across various TES systems, including thermal storage for peak heat demand management, indirect-contact latent heat storage for solar energy, and direct-contact thermal storage in heat exchangers. Thermal energy storage (TES) is crucial for improving energy efficiency, yet phase change materials (PCMs) often exhibit low thermal conductivity. To overcome this, studies have explored enhancing PCM properties using nanoparticles, optimized container designs, and cascaded thermal storage (CTS) systems. Experimental research on multi-walled carbon nanotube (MWCNT)-based nanofluids highlights significant thermal conductivity improvements through nanoparticle dispersion and temperature control, achieving a peak conductivity of 0.988 W/mK. Cascaded PCM storage in solar water collectors (SWCs) has been found to enhance exergy efficiency and energy utilization. Optimized container configurations, such as finned structures and triplex tube heat storage units, further accelerate PCM melting and solidification. Research indicates that rectangular PCM containers and longitudinal fins outperform other geometries in heat transfer efficiency. Moreover, fins alone prove more effective than hybrid fin-nanoparticle designs for improving thermal performance. Integrating multiple enhancement techniques—such as fins, expanded graphite, and heat pipes—can further elevate TES efficiency. Future investigations should prioritize large-scale application, long-term stability, and

Abbreviations: Al, Aluminium; Al_2O_3, Aluminium Oxide; CFD, Computational Fluid Dynamics; Cu, Copper; EPCM, Encapsulated Phase Change Material; hnpcm, Hybrid Nano Phase Change Material; HTF, Heat Transfer Fluid; np, Nanoparticles; PE, Pentaerythritol; PCM, Phase Change Material; TCR, Thermal Contact Resistance; TES, Thermal Energy Storage; Zn, Zinc.

* Corresponding authors.
E-mail addresses: jayaprakash.aero@sathyabama.ac.in (J. V), nandagopal.kaliappan@haramaya.edu.et (N. Kaliappan).

https://doi.org/10.1016/j.rineng.2025.104899
Received 23 November 2024; Received in revised form 22 March 2025; Accepted 10 April 2025
Available online 14 April 2025

thermodynamic optimization to develop sustainable storage solutions [2–4].

Research by Verma and Singal highlights that while numerous phase change materials with distinct thermophysical properties have been investigated for cooling and heating applications, consistent success has often been elusive [5].

To address energy storage limitations, researchers have explored systems integrating active and passive PCMs across multiple phases. Additionally, efforts have been made to enhance the thermophysical properties of PCMs through the use of micron-sized additives, but these have not yet achieved the desired improvements in heat transfer characteristics [6].

Paraffin is a member of the organic PCM class, which is widely accessible and extensively utilised in TES. When paraffin is employed for thermal storage in thermoelectric sensors, its low thermal conductivity impacts the thermal energy gain and release rate. The TES system needs an efficient storage medium for heating and cooling thermal energy applications. The latent and sensible heat of the material and the amount of energy collected and discharged are what the TES system depends on. Therefore, Farid et al.. demonstrated that increasing heat conductivity can increase TES. Both theoretical and experimental studies have shown that nanomaterials can be efficiently distributed throughout a fluid or composite to modify its thermophysical properties to suit the demands of different thermal-energy applications [7]. Roget et al.. investigated the characteristics of mixed eutectic compositions of solid-liquid PCMs. However, their experimental measurements did not include key thermal properties such as specific heat and thermal conductivity [8]. The melting temperatures and densities of the various compositions were examined in Ne-PCM samples based on cyclohexane made using CuO nanoparticles at different mass concentrations [9]. According to their findings, samples in the liquid phase improved as the number of nanoparticles increased, whereas samples in the solid phase showed a non-monotonic augmentation at concentrations higher than 2 % [10].

Using an Al_2O_3 water-based nanofluid under steady-state circumstances in the engine-cooling system improved the efficiency. With a 1 % volume fraction addition, the Al_2O_3 nanofluid enhanced the cooling system's efficiency by 30 % [11]. Yu et al. investigated the impact of carbon nanomaterials on the thermal conductivity of liquid paraffin-based suspensions. The findings demonstrated that as the carbon addition loading grows, the suspensions' thermal conductivity also rises, with the additives' size and form significantly impacting how much the thermal conductivity increases overall [12]. Integrating TES with collector systems can dramatically improve efficiency and heat transfer performance. In particular, the thermal conductivity of paraffin-based PCMs in collector systems can be enhanced using nanocomposites. Numerous studies have experimentally investigated nanofluids' thermal conductivity, focusing on using metal oxides and nanotubes as additives [13]. Al_2O_3 and CuO are the most commonly used metal oxide nanoparticles in experimental research [14].

In nanocomposite phase change materials, pentaerythritol (PE), a solid-solid PCM, has been combined with aluminum nitrate nanoparticles, which serve as self-nucleating agents to enhance crystallisation kinetics. Experimental results indicate that PE containing 3.0 wt % nano-AlN exhibits solid-solid phase change behavior during heating without supercooling during the cooling process, maintaining consistent phase change temperatures [15]. Zheng et al.. explored methods to enhance convective heat transfer in solar collector systems utilizing encapsulated phase change materials (EPCMs). In these systems, the heat transfer fluid (HTF) circulates through the EPCM capsules, effectively transferring thermal energy during multiple charging and discharging cycles. Their findings demonstrated that EPCM-based systems efficiently store and retrieve thermal energy, enhancing overall energy management [16].

Erythritol and xylitol, both polyol-based PCMs, are known for their high energy storage densities due to their chemical structures, which feature multiple high-polarity hydroxyl groups [17]. However, these materials suffer from relatively low thermal conductivity [18], which limits their heat transfer efficiency with the surrounding heat exchange medium. This, in turn, adversely impacts the latent heat storage system's ability to effectively store and release heat during cyclic phase transitions. As a result, enhancing the thermal conductivity of erythritol has become a critical area of research. In recent years, considerable efforts have been made to improve the thermal conductivities of conventional PCMs. One approach has involved the development of PCM composites by integrating PCMs with highly conductive porous metal foams. Li et al. [16] impregnated erythritol into rough hydrophilic copper (Cu) foam to make composites. Cu foam-templated composites had five times the heat conductivity of pure erythritol. These materials enabled 85.8 % heat retrieval in a solar-thermal energy storage system. Polyol PCM/metal foam composite research is restricted despite these promising results. In addition, the integration of phase change materials (PCMs) with advanced thermal management techniques has gained significant attention for enhancing energy storage and dissipation efficiency across various applications. Chibani et al. explore hybrid nano-PCMs' performance in sonochemical reactors and solar panel cooling systems, focusing on their synthesis, heat transfer behavior, and optimization strategies [19,20].

A computational fluid dynamics (CFD) approach using ANSYS Fluent® was employed to analyze the interaction between PCMs and external heat sources. In sonoreactors, PCMs replaced conventional water-based cooling, demonstrating effective temperature stabilization and energy absorption, particularly at an optimal liquid height of 15.3 cm. In solar panel applications, a comparative study of Gallium, Paraffin RT35HC, and $CaCl_2 \cdot 6H_2O$ revealed that Gallium provided the best cooling performance and electrical efficiency, whereas $CaCl_2 \cdot 6H_2O$ showed weaker thermal regulation [21]. Further enhancement was achieved by integrating fins with PCMs, accelerating the melting process and heat dissipation. Numerical simulations indicated that fins increased PCM melting efficiency by up to 43.5 % (at 1000s) and 66 % (at 2000s) compared to systems without fins. A sono-PCM reactor approach was introduced, replacing energy-intensive cryothermostats with nano-enhanced PCMs for sustainable and cost-effective thermal management [22]. Both modeling and experimental studies have investigated the melting behavior and thermophysical properties of PCM/metal foam composites [23,24]. Jin et al.. studied the influence of copper foam pore size on the melting rate and thermal conductivity of paraffin/copper foam composites. At a 30 K superheated wall temperature, composites with 30 and 50 ppi pore sizes exhibited similar melting rates, significantly faster than those with 15 ppi foam. While smaller pore sizes can enhance the thermal conductivity of PCM/metal foam composites, their infrared thermographic analysis revealed significant temperature differences between the paraffin and metal foam during melting, indicating the presence of high thermal contact resistances (TCRs) [24].

The previous investigation into PCMs has made significant advancements; however, a key limitation persists in their overall heat transfer efficiency. While nanoparticle doping has shown promise in addressing this issue, existing research lacks comprehensive studies on the combined effects of multiple nanoparticles—such as copper (Cu), aluminum (Al), and zinc (Zn)—on the thermo-physical properties and performance of PCMs like erythritol and xylitol. Additionally, there has been limited exploration of hybrid nano-PCMs in multi-temperature thermal energy storage systems, which are essential for real-world applications. As a result, further research is needed to bridge these gaps and enhance the practical implementation of these materials.

This study overcomes these limitations by synthesizing hybrid nano-PCMs through a two-step process, incorporating 1.5 % Cu, Al, and Zn nanoparticles into erythritol and xylitol. It introduces an innovative approach to enhancing phase change materials (PCMs) for thermal energy storage, addressing the inherent low thermal conductivity and limited heat transfer efficiency of conventional PCMs. The developed hybrid nano-PCMs exhibit significantly improved thermo-physical properties, including higher thermal conductivity, diffusivity, density, and specific heat capacity. Their performance is uniquely evaluated in a multi-temperature storage system using Therminol-66 as the heat transfer fluid, offering comprehensive insights into their practical application. The study primarily focuses on optimizing thermo-physical properties to enhance overall thermal efficiency while also assessing heat transfer rates and energy performance across diverse temperature ranges. Systematic evaluation and validation against the base PCMs provide a detailed understanding of their effectiveness. By identifying the most efficient hybrid nano-PCMs in terms of thermal and performance characteristics, this research contributes valuable knowledge toward the development of scalable and sustainable advanced thermal energy storage solutions.

2. Materials and methods

2.1. Synthesis method

The erythritol and xylitol nanocomposites were synthesized using a two-step process. Nanoparticles of aluminum (Al), copper (Cu), and zinc (Zn) with an average size of 40 nm and a purity of 99.9 %, sourced from TSR Instruments & Solutions, India, were used in the study. The nanoparticles were incorporated into liquid erythritol and xylitol without surfactants, maintaining a fixed weight fraction of 1.5 %. A precision mass balance (accurate to 0.1 mg) was employed to ensure accurate sample preparation, with the weight percentages calculated based on the mass ratio. Initially, the nanoparticles were sheared into the liquid phase of erythritol and xylitol using a magnetic stirrer at a constant temperature for 30 min. Erythritol was preheated to 120 °C and xylitol to 90 °C on a hot plate, and both were subsequently degassed in a vacuum oven at 105 °C for 2 h. To ensure proper dispersion, ultrasonic immersion sonication (40 kHz, 200 W) was applied for five hours, maintaining the same preheating temperatures throughout the process. This method ensured a uniform distribution of nanoparticles in the resulting nanocomposites.

2.2. Thermophysical properties

Thermophysical properties are measured by hot disk-thermal analyser TPS 2500S. 5 g of the sample is used for the characterisation with 8 mm thickness and 28 mm diameter. Each sample is conducted 3 times, and the average of these values is tabulated with an accuracy level of ± 5 %. Thermophysical properties of hybrid nano PCMs are calculated based on the following Eqs. (1–4):

The density of hybrid nano PCMs is typically calculated using the rules of mixtures [25]:

$$\rho_{\mathrm{hnpcm}} = (1-\phi)\rho_{\mathrm{pcm}} + \phi\rho_{\mathrm{np}} \tag{1}$$

where ϕ is volume fractions of nanoparticles, ρ_{pcm} is density of PCM, ρ_{np} is density of nano particle, and ρ_{hnpcm} is density of hybrid nano PCM.

The thermal conductivity of hybrid nano PCMs is typically calculated using the Maxwell model [26]:

$$\mathrm{K_{hnpcm}} = \mathrm{K_{pcm}}\left(\mathrm{K_{np}} + 2\mathrm{K_{pcm}} + \phi\left(\mathrm{K_{pcm}} - \mathrm{K_{np}}\right)\right) \Big/ \left(\mathrm{K_{np}} + 2\mathrm{K_{pcm}} - 2\phi\left(\mathrm{K_{pcm}} - \mathrm{K_{np}}\right)\right) \tag{2}$$

$\mathrm{K_{pcm}}$ is the thermal conductivity of PCM, Knp is the thermal conductivity of nanoparticles, and Khnpcm is the thermal conductivity of hybrid nano PCM.

The thermal diffusivity of hybrid nano PCMs is typically calculated as:

$$\alpha_{\mathrm{hnpcm}} = \left(\mathrm{K_{hnpcm}}\right) \Big/ \left(\rho_{\mathrm{hnpcm}}\mathrm{Cp_{hnpcm}}\right) \tag{3}$$

The specific heat capacity of hybrid nano PCMs is typically calculated as [25]:

$$\mathrm{Cp_{hnpcm}} = (1-\phi)\mathrm{Cp_{pcm}} + \phi\mathrm{Cp_{np}} \tag{4}$$

$\mathrm{Cp_{pcm}}$ is the specific heat capacity of PCM, Cpnp is the specific heat capacity of nanoparticles, and Cphnpcm is the specific heat capacity of hybrid nano PCM.

2.3. Experimentation

The experimental setup comprises a heat recovery unit, a circulating pump, two latent heat thermal energy storage tanks (PCHES 1 and 2), an oil tank, and a solar dish collector, as shown in Fig. 1. The solar beams are directed towards the receiver, where a 3 m^2 solar dish collector with a 96 % reflectivity aluminium-glazed reflector surface is employed to circulate the HTF. Oil storage tanks, heat recovery units, and heat storage tanks have 0.06 m thick glass wool insulation applied to their exteriors to prevent heat loss. Pipelines used for circulation are insulated with 0.03 m thick cotton rope. To ensure the leak-proof nature of the system, numerous leak tests have been conducted in the storage tanks and pipelines. Therminol-66 is the HTF selected for the analysis. The model system has been constructed to store and release energy of about 4000 kJ using PCM at different temperatures. Due to their high latent heat of fusion, PCMs like erythritol and xylitol store significantly more solar energy per unit mass or volume than other materials. In the energy storage system, these PCMs are arranged in descending order of their melting temperatures within two separate storage tanks: Tank 1 for erythritol and Tank 2 for xylitol. Heat transfer fluid (HTF) from the solar receiver is directed into these latent heat storage containers during operation. As the HTF flows through Tanks 1 and 2, it transfers heat to the PCMs, causing them to absorb the energy, melt, and transition from solid to liquid, effectively storing thermal energy. This procedure is continued until all PCMs have melted, which is known as the charging process. Tanks 2 and 1 reverse the direction of HTF flow to permit low-temperature HTF to pass through when the sun isn't shining. As the HTF moves through the PCM tanks, its temperature rises gradually, which causes the PCMs to lose energy and undergo a phase change from liquid to solid. This process is repeated until the PCM mass is in the solid state, known as the "discharging process". Thermocouples were used to measure the HTF's temperature at various intervals to evaluate the system's performance.

2.4. Performance parameter analysis

The parameters considered for evaluating system performance are the energy in the HTF from PTC, PCMs (charging), the energy delivered by the PCMs during the discharging process, and the system's overall energy efficiency with the use of finned encapsulated PCMs. Eq. (5) and 6 was developed by Gong and Mujumdar (1997) to determine the heat release rate $Q_{c.\ PCM1}$ & $Q_{c.PCM2}$ of HTF is flowing through Erythritol (PCM1) and Xylitol (PCM2) [26,27].

$$Q_{c.PCM1} = \dot{m}\ C_P\ (T_{c1} - T_{c2}) \tag{5}$$

$$Q_{c.PCM2} = \dot{m}\ C_P\ (T_{c2} - T_{c3}) \tag{6}$$

Energy stored in the PCMs $E_{c.PCMs}$ and charging efficiency $\eta_{charging}$ of the system has been calculated by Eqs. (7) and (8), where A_C is the area of the collector and I_b is the solar beam radiation.

$$E_{c.PCMs} = Q_{c.PCM1} + Q_{c.PCM2} \tag{7}$$

$$\eta_{charging} = \frac{E_{c.PCMs}}{A_C * I_b} \tag{8}$$

To find the heat release rate or energy release rate from the PCMs during the discharging process, the HTF flow direction has been reversed and passed through PCM2 and PCM1. The energy release rate of PCM2 ($Q_{d.PCM2}$) and PCM1 ($Q_{d.PCM1}$) Eqs. (9) and (10) are calculated during discharging. The T_{d3} and T_{d2} is referred to as the outlet

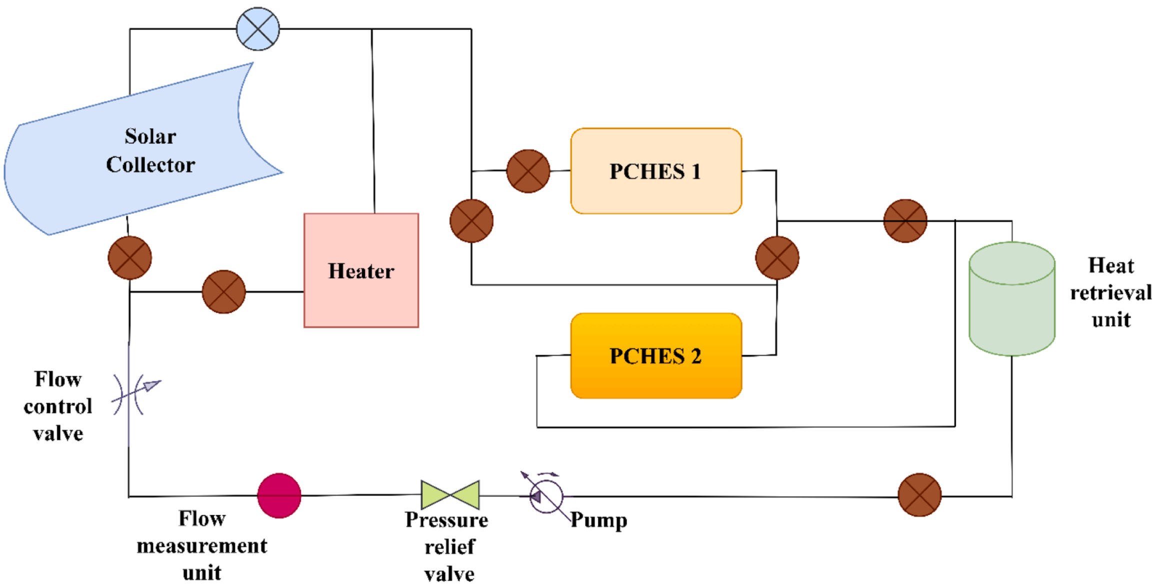

Fig. 1. Experimental setup of multi-temperature PCMs.

temperature of HTF from PCM tanks 2 and 1, respectively. The T_{d1} is referred to as the inlet temperature of HTF to the PCM tank 1.

$$Q_{d.PCM2} = \dot{m}\ C_P\ (T_{d3} - T_{d2}) \tag{9}$$

$$Q_{d.PCM1} = \dot{m}\ C_P\ (T_{d2} - T_{d1}) \tag{10}$$

The total energy release rate of PCMs $E_{d.PCMs}$ and discharging efficiency $\eta_{discharging}$ Eqs. (11) and (12) of the system are calculated.

$$E_{d.PCMs} = Q_{d.PCM2} + Q_{d.PCM2} \tag{11}$$

$$\eta_{discharging} \tag{12}$$

The total energy efficiency of the system is calculated as the product of the energy efficiencies during both the charging and discharging phases. This relationship is expressed in Eq. (13).

$$\eta_{overall} = \eta_{charging} * \eta_{discharging} \tag{13}$$

3. Results

The experimentation and thermo-physical results are discussed for all the types of PCMs, such as Erythritol (Er), Xylitol (Xy), Erythritol doped with copper, aluminium, and zinc as Er- Cu, Er-Al, and Er-Zn, respectively, and xylitol doped with copper, aluminium, and zinc as Xy-Cu, Xy-Al, and Xy-Zn, respectively.

3.1. Effect of thermo-physical properties

Table 1 lists the thermo-physical properties of all pure materials, such as erythritol, xylitol, Cu-nanoparticle, Al-nanoparticle, and Zn-nanoparticle [28]. Based on Table 1, erythritol and xylitol thermal conductivity is too low, such as 0.2 and 0.35 $Wm^{-1}K^{-1}$, but it has high specific heat capacities as 3.94 and 3.70 MJ/m^3K, respectively. However, the thermal conductivity of Cu, Al, and Zn has high thermal conductivity with low specific heat capacity. So, to enhance the thermal conductivity of erythritol and xylitol PCMs, doping of this nanoparticle is done using a two-step synthesis method at 1.5 wt.%. The resulting hybrid PCMs, such as Er-Cu, Er-Al, Er-Zn, Xy-Cu, Xy-Al, and Xy-Zn, have the increased thermal conductivity and specific heat capacity listed in Table 2.

Fig. 2 shows the density and specific heat interpretation for all the hybrid PCMs with the parent PCM. It indicates that erythritol-Cu and xylitol-Cu have the highest densities and specific heat, 1616.3 and 1695 Kg/m^3, 4.493 and 4.134 MJ/m^3K, respectively. This indicates that density and specific heat capacities are increased due to the doping of nanoparticles in parent PCMs. The density and specific heat of erythritol PCM follow the Er-Cu > Er-Al > Er-Zn trend, whereas xylitol PCM follows the Xy-Cu > Xy-Al > Xy-Zn trend, respectively. Fig. 3 shows the thermal conductivity and thermal diffusivity interpretation for all the hybrid PCMs with the parent PCM. The thermal conductivity of parent PCMs such as erythritol and xylitol are 0.2 and 0.35 $Wm^{-1}K^{-1}$, measured using the hot disk-thermal constant analyser. After doping nanoparticles with parent PCMs, the thermal conductivity of all hybrid PCMs is increased without respect to nanoparticles, as shown in Fig. 3. In

Table 1
Thermophysical Properties of the PCMs and nanomaterials.

PCM	Melting-Point (°C)	Density (Kg/m^3)	Thermal-Conductivity ($Wm^{-1}K^{-1}$)	Thermal-Diffusivity ($*10^{-6}\ m^2/s$)	Specific-Heat (MJ/m^3K)
Erythritol	121–123	1450	0.2	0.10	3.94
Xylitol	92–95	1525	0.35	0.15	3.70
Cu - metal	NA	8960	401	116	0.385
Al - metal	NA	2700	238	93.4	0.945
Zn - metal	NA	7130	112	41.2	0.385

Table 2
Thermophysical Properties of the PCMs and Hybrid PCMs.

PCM	Melting-Point (°C)	Density (Kg/m^3)	Thermal-Conductivity ($Wm^{-1}K^{-1}$)	Thermal-Diffusivity ($*10^{-6}\ m^2/s$)	Specific-Heat (MJ/m^3K)
Erythritol	121–123	1450	0.2	0.10	3.94
Xylitol	92–95	1525	0.35	0.15	3.70
Erythritol-Cu	119–120	1616.3	0.2698	0.1504	4.493
Xylitol-Cu	90–94	1695	0.4215	0.210	4.134
Erythritol-Al	118–121	1549	0.2487	0.167	4.148
Xylitol-Al	90–93	1632.5	0.3891	0.209	3.914
Erythritol-Zn	115–119	1560.5	0.3012	0.2291	3.159
Xylitol-Zn	87–90	1639.2	0.4496	0.1901	3.301

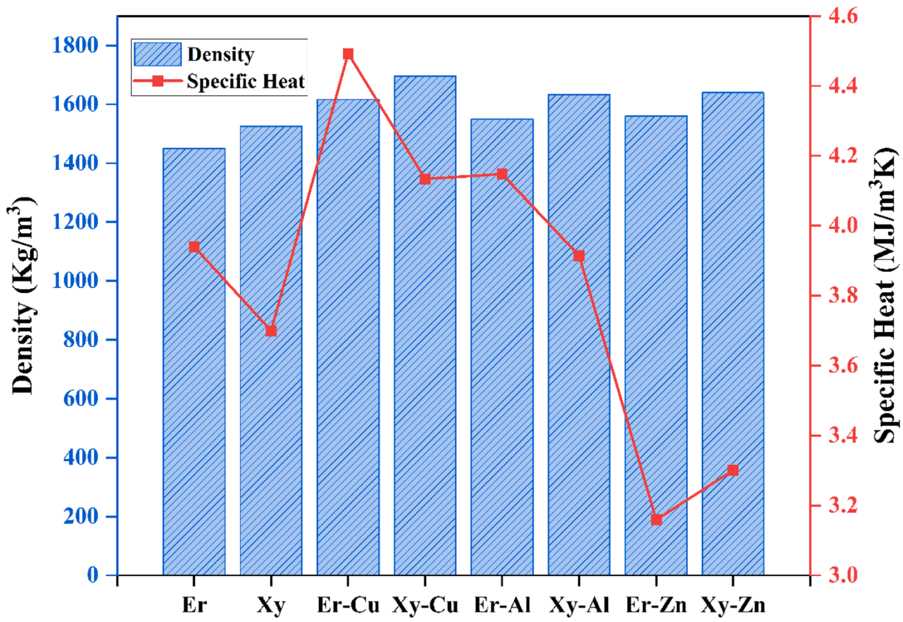

Fig. 2. Density Vs specific heat for hybrid PCMs.

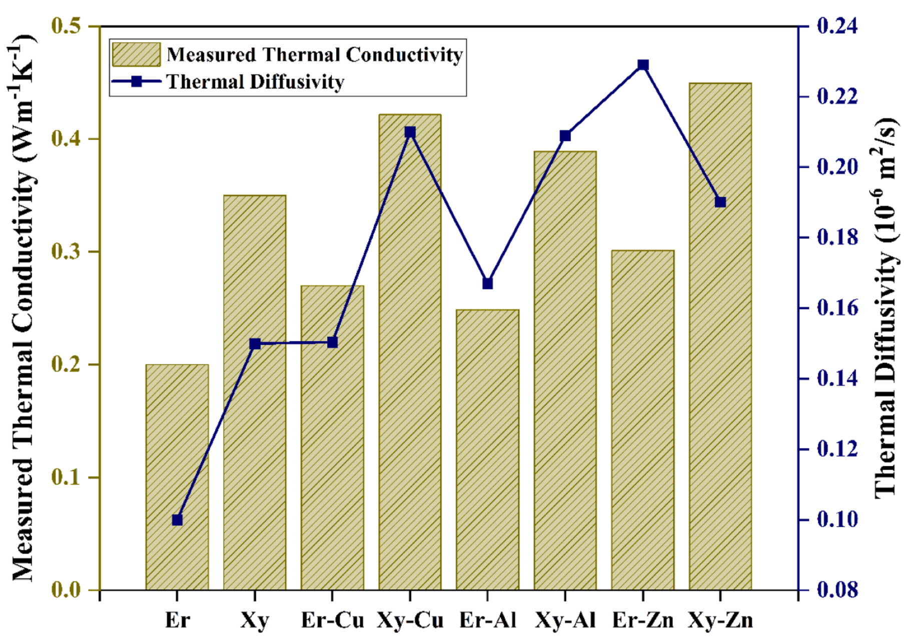

Fig. 3. Thermal conductivity Vs thermal diffusivity for hybrid PCMs.

comparison among the nanoparticles, Erythritol-Zn and Xylitol-Zn showed the highest thermal conductivity of 0.3012 and 0.4496 $Wm^{-1}K^{-1}$. From the results, Zn-nanoparticle shows increased thermal conductivity. Er-Zn has a 50.6 % increased thermal conductivity than the parent erythritol PCM, and Xy-Zn has a 28.45 % higher thermal conductivity than the parent xylitol PCM. This is because as the interfacial contact ratio increases, the thermal conductivity of the erythritol and xylitol PCMs will increase. So, the interfacial contact will always be greater in the trend of Zn > Al > Cu [15]. So, the Er-Zn and Xy-Zn's thermal conductivity is high compared to other hybrid PCMs, but these also have higher thermal conductivity than the parent PCMs. The thermal diffusivity of hybrid PCMs is shown in Fig. 3, which indicates that the thermal diffusivity for Zn-based PCMs is higher than other hybrid PCMs. Still, these hybrid PCMs have also increased their property more than the parent PCM. Thermal diffusivity is a measure of thermal energy transport related to the stability of thermal energy storage [28]. The results show that hybrid PCMs tend to store and transfer heat energy more than the parent PCMs; Er-Zn and Xy-Zn have the highest tendency due to increased thermal diffusivity.

3.2. Charging and discharging cycle

The experimentation is carried out using a charging and discharging process. The charging process is carried out for 400 and 250 min with the 10-minute intervals for erythritol and xylitol-based PCMs, respectively. Fig. 4 shows the charging cycle for erythritol and its hybrid PCMs, indicating that after 70 mins of charging, there are no significant changes in the temperature among the PCMs; after 70 mins of charging, there was a gradual increase observed from all the PCMs still 200 mins. At 200 mins, nearly all the PCMs start changing their phases as a point of

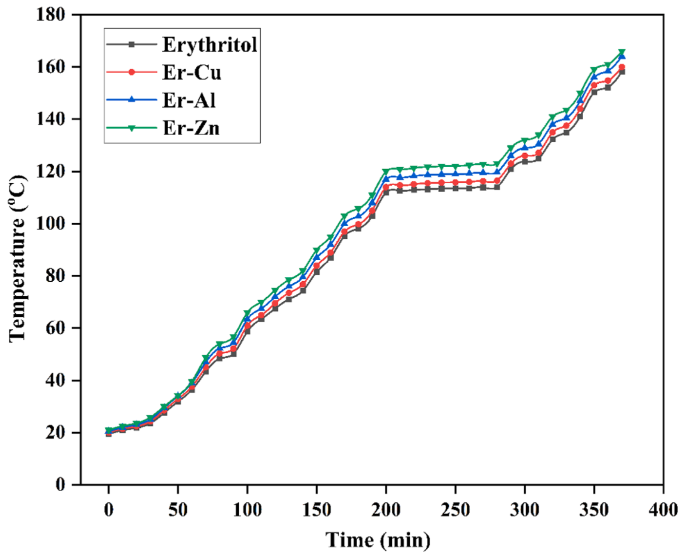

Fig. 4. Charging process of Erythritol and its hybrid PCMS.

fusion. From 200 mins to 300 mins, it undergoes the phase change energy storage process. After it undergoes a steady state of heat with energy storage. Among the hybrid PCMs, Er-Zn undergoes the phase earlier than other PCMs, such as Er-Al and Er-Cu, with high latent heat energy storage. Fig. 5 shows the discharging cycle for erythritol and its hybrid PCMs, indicating that Er-Zn transfers its energy and attains its original state compared to another type of erythritol PCMs [16].

Figs. 6 and 7 illustrate the charging and discharging cycles for Xylitol and its hybrid PCMs, providing insights into their thermal behavior and energy storage efficiency. The charging cycle (Fig. 6) demonstrates that within the first 30 min, there are no significant temperature variations among the PCMs, indicating similar initial thermal responses. However, beyond this point, a gradual temperature increase is observed across all PCMs, continuing steadily until approximately 100 min. At this stage, nearly all PCMs reach their fusion point, initiating phase transition and latent heat absorption. The phase change energy storage process occurs between 100 and 150 min, during which the PCMs effectively store thermal energy. Eventually, they reach a steady-state condition, maintaining stored energy without further temperature fluctuations.

Among the hybrid PCMs, Xy-Zn exhibits an earlier phase transition compared to Xy-Al and Xy-Cu, indicating a lower supercooling effect and improved thermal conductivity, likely due to the enhanced nucleation properties of Zn nanoparticles. Additionally, Xy-Zn demonstrates higher latent heat storage capacity, making it a more efficient thermal energy storage material.

Fig. 7 depicts the discharging cycle, revealing that Xy-Zn releases its stored energy and returns to its original state more efficiently than the other hybrid PCMs. This suggests that Zn nanoparticles enhance heat transfer rates during both charging and discharging processes, reducing thermal resistance and improving overall energy retrieval. The superior thermal performance of Xy-Zn makes it a promising candidate for applications requiring rapid thermal response and high energy storage efficiency in multi-temperature thermal energy storage systems [17].

3.3. Heat transfer rate

Fig. 8 shows the heat transfer rate of erythritol and its hybrid PCMs. The heat gain for Er, Er-Cu, Er-Al and Er-Zn are 3123.6 KJ, 3289.34 KJ, 3465.1 KJ, and 3596.73 KJ. Among these hybrid PCMs, Er-Zn has the highest heat gain compared to other hybrid and parent erythritol PCMs. The increasing order of heat gain is Er $<$ Er-Cu $<$ Er-Al $<$ Er-Zn; this shows the interfacial contact ratio is higher for Er-Zn, and the trend is also followed in the heat loss. So, among the PCMs, the Er-Zn Nanohybrid PCM has the maximum tendency to store heat energy.

Fig. 9 shows the heat transfer rate of xylitol and its hybrid PCMs. The heat gain for Xy, Xy-Cu, Xy-Al and Xy-Zn are 1923.6 KJ, 2146.3 KJ, 2312.65 KJ, and 2629.54 KJ. Among these hybrid PCMs, Xy-Zn has the highest heat gain compared to other hybrid and parent erythritol PCMs. The increasing order of heat gain is Xy $<$ Xy-Cu $<$ Xy-Al $<$ Xy-Zn; this shows that the interfacial contact ratio is higher for Xy-Zn, and the same trend is followed in the heat loss. So, among the PCMs, the Xy-Zn Nanohybrid PCM has the maximum tendency to store heat energy. Compared to thermal conductivity, thermal diffusivity, and heat transfer rate results, the nanohybrid PCMs exhibit better energy storage capacity. Among the nanohybrid PCMs, Er-Zn and Xy-Zn have excellent energy

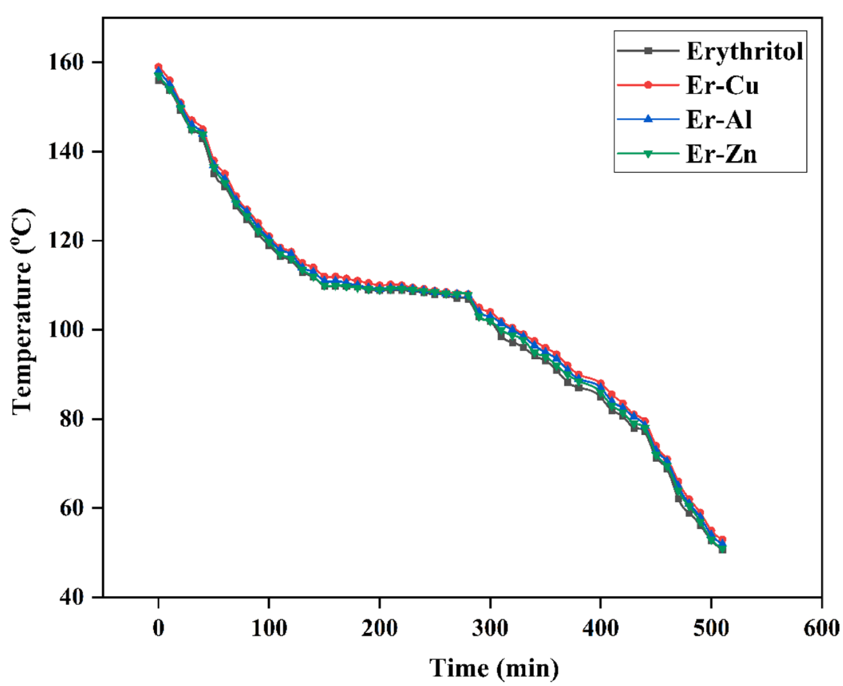

Fig. 5. Discharging process of Erythritol and its hybrid PCMS.

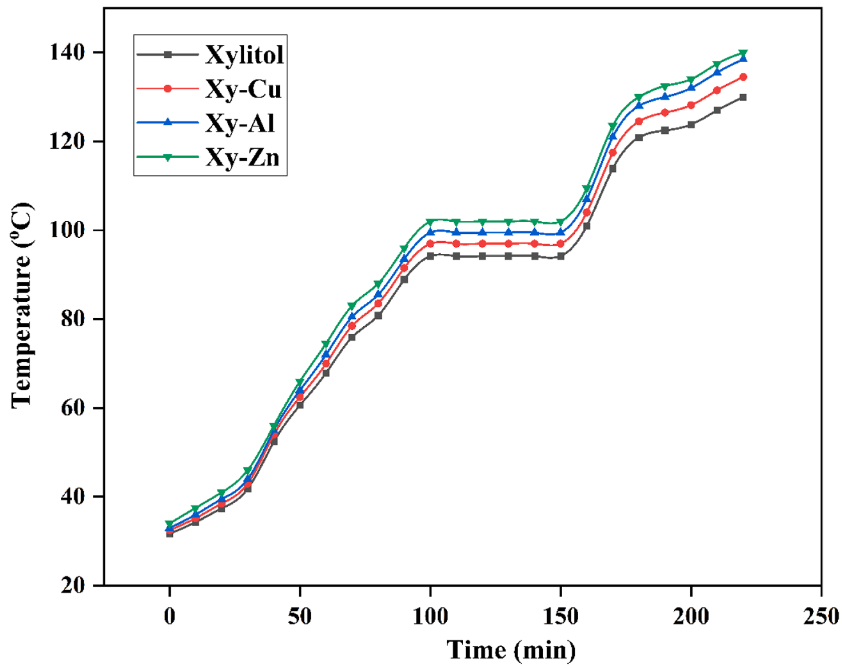

Fig. 6. Charging process of Xylitol and its hybrid PCMs.

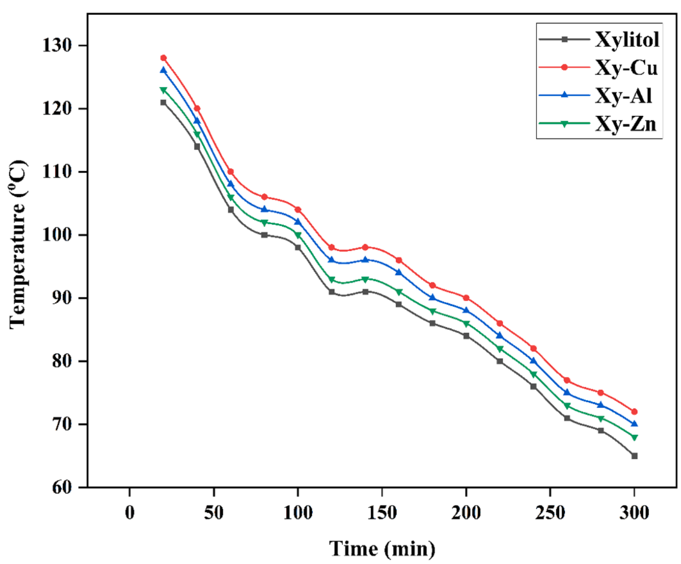

Fig. 7. Discharging process of Xylitol and its hybrid PCMs.

storage capacity due to high thermal conductivity and diffusivity.

4. Conclusion

This study results highlight the potential of hybrid nano-PCMs for improving the efficiency and effectiveness of thermal energy storage systems across a range of temperature applications. The superior thermal and performance characteristics of Er-Zn and Xy-Zn, in particular, position them as promising candidates for advanced energy storage solutions. Future studies should focus on scaling up the synthesis process, long-term stability assessments, and exploring broader applications to further enhance the practical utility of these materials.

This research successfully synthesized and evaluated hybrid nanophase change materials (nano-PCMs) based on erythritol and xylitol doped with copper (Cu), aluminum (Al), and zinc (Zn) nanoparticles at a 1.5 % weight ratio. The developed nano-PCMs—Er-Cu, Er-Al, Er-Zn, Xy-Cu, Xy-Al, and Xy-Zn—were systematically characterized for their thermo-physical properties and assessed for their effectiveness in multi-temperature thermal energy storage systems.

The findings demonstrate that nanoparticle doping significantly enhances key thermal properties, including thermal conductivity, diffusivity, density, and specific heat capacity, primarily due to the increased interfacial contact ratio and improved phonon transport mechanisms facilitated by the embedded nanoparticles. Among the tested materials, Er-Zn and Xy-Zn exhibited the most superior thermal performance, achieving the highest thermal conductivities of 0.3012 $Wm^{-1}K^{-1}$ and 0.4496 $Wm^{-1}K^{-1}$, respectively. Performance analysis further revealed substantial improvements in the heat transfer rates of all hybrid nano-PCMs, with Er-Zn and Xy-Zn attaining peak heat transfer values of 3596.73 KJ and 2629.54 KJ, respectively. These results establish the potential of hybrid nano-PCMs in enhancing the efficiency of thermal energy storage systems across diverse temperature applications. Despite these promising outcomes, further research is necessary to bridge existing gaps and advance the practical deployment of these materials. Future studies will focus on long-term stability and degradation analysis by optimization of nanoparticle concentration.

CRediT authorship contribution statement

Jayaprakash V: Formal analysis, Data curation, Conceptualization. **Ganesan S:** Methodology, Investigation, Funding acquisition. **Beemkumar N:** Software, Resources, Project administration. **Sunil Kumar M:** Project administration, Funding acquisition. **Kamakshi Priya K:** Resources, Formal analysis. **Nandagopal Kaliappan:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

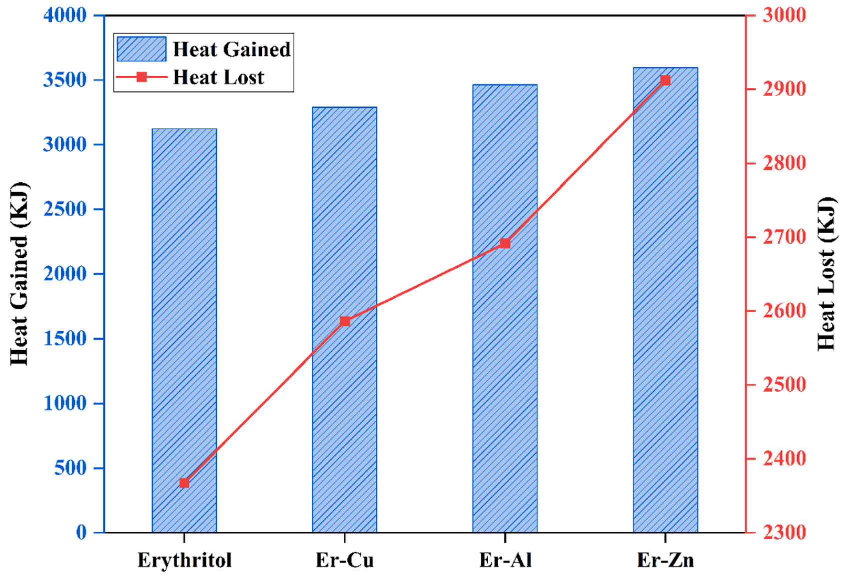

Fig. 8. Heat gained and loss for erythritol and its hybrid PCMs.

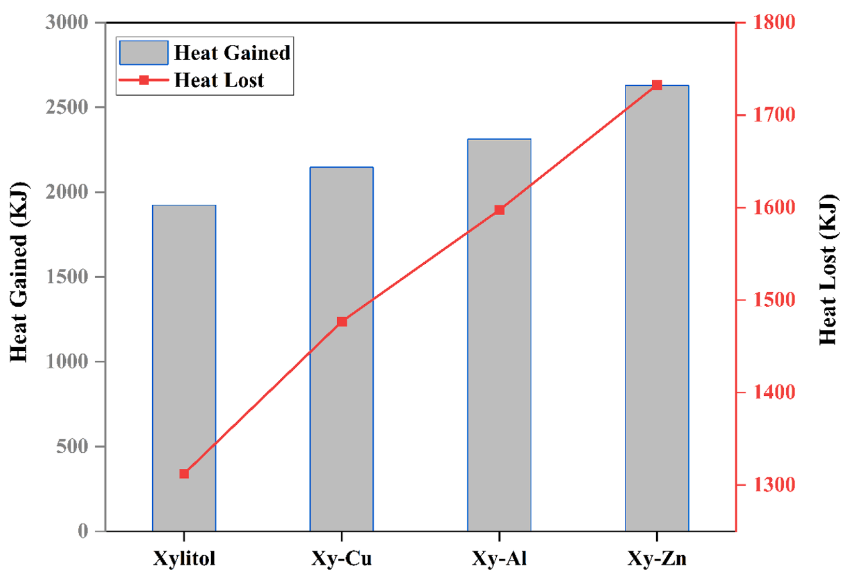

Fig. 9. Heat gained and loss for xylitol and its hybrid PCMs.

Data availability

No data was used for the research described in the article.

References

[1] A. Joulin, Z. Younsi, L. Zalewski, S. Lassue, D.R. Rousse, J.-P. Cavrot, Experimental and numerical investigation of a phase change material: thermal-energy storage and release, Appl. Energy 88 (2011) 2454–2462, https://doi.org/10.1016/j.apenergy.2011.01.036.

[2] K. Karthik, R. Rohith Renish, I. Irfan Ahmed, T. Niruban Projoth, Free vibration test for damping characteristics of hybrid polyester matrix composite with carbon particles, Nano Hybrid. Compos. 11 (2016) 1–6, https://doi.org/10.4028/www.scientific.net/nhc.11.1.

[3] D. Christopher Selvam, Y. Devarajan, T. Raja, S. Vickram, Advancements in water electrolysis technologies and enhanced storage solutions for green hydrogen using renewable energy sources, Appl. Energy 390 (2025) 125849, https://doi.org/10.1016/j.apenergy.2025.125849.

[4] M.E. Zayed, J. Zhao, W. Li, A.H. Elsheikh, A.M. Elbanna, L. Jing, A.E. Geweda, Recent progress in phase change materials storage containers: geometries, design considerations and heat transfer improvement methods, J. Ene. Sto. 30 (2020) 101341, https://doi.org/10.1016/j.est.2020.101341.

[5] P. Verma, S.K.Singal Varun, Review of mathematical modeling on latent heat thermal energy storage systems using phase-change material, Renew. Sustain. Energy Rev. 12 (2008) 999–1031, https://doi.org/10.1016/j.rser.2006.11.002.

[6] S. Manikandan, Y. Devarajan, S. Vickram, Advancing thermal energy storage with industrial and agricultural waste-derived phase change materials: A path towards sustainable energy systems, Process Saf. Environ. Prot. 198 (2025) 107068, https://doi.org/10.1016/j.psep.2025.107068.

[7] M.M. Farid, A.M. Khudhair, S.A.K. Razack, S. Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Convers. Manag. 45 (2004) 1597–1615, https://doi.org/10.1016/j.enconman.2003.09.015.

[8] F. Roget, C. Favotto, J. Rogez, Study of the KNO3–LiNO3 and KNO3–NaNO3–LiNO3 eutectics as phase change materials for thermal storage in a low-temperature solar power plant, Sol. Energy 95 (2013) 155–169, https://doi.org/10.1016/j.solener.2013.06.008.

[9] L. Fan, J.M. Khodadadi, An experimental investigation of enhanced thermal conductivity and expedited unidirectional freezing of cyclohexane-based nanoparticle suspensions utilized as nano-enhanced phase change materials (NePCM), Int. J. Therm. Sci. 62 (2012) 120–126, https://doi.org/10.1016/j.ijthermalsci.2011.11.005.

[10] W. Yu, H. Xie, Y. Li, L. Chen, Experimental investigation on thermal conductivity and viscosity of aluminum nitride nanofluid, Particuology 9 (2011) 187–191, https://doi.org/10.1016/j.partic.2010.05.014.

[11] C.S. Damian, Y. Devarajan, R. Jayabal, T. Raja, Enhancing marine diesel engine compatibility with sustainable fuels: Key factors and adjustments, Mar. Pollut. Bull. 215 (2025) 117836, https://doi.org/10.1016/j.marpolbul.2025.117836.
[12] Z.-T. Yu, X. Fang, L.-W. Fan, X. Wang, Y.-Q. Xiao, Y. Zeng, X. Xu, Y.-C. Hu, K.-F. Cen, Increased thermal conductivity of liquid paraffin-based suspensions in the presence of carbon nano-additives of various sizes and shapes, Carbon N. Y. 53 (2013) 277–285, https://doi.org/10.1016/j.carbon.2012.10.059.
[13] A.-K.H. Hussain, L.C. Saw, L. Afolabi, Review on nanomaterials for thermal energy Storage technologies, Nanosci. Nanotechnology-Asia 3 (2013) 60–71, https://doi.org/10.2174/22113525113119990011.
[14] T.-P. Teng, Thermal conductivity and phase-change properties of aqueous alumina nanofluid, Energy Convers. Manag. 67 (2013) 369–375, https://doi.org/10.1016/j.enconman.2012.12.004.
[15] P. Hu, P.-P. Zhao, Y. Jin, Z.-S. Chen, Experimental study on solid–solid phase change properties of pentaerythritol (PE)/nano-AlN composite for thermal storage, Sol. Energy 102 (2014) 91–97, https://doi.org/10.1016/j.solener.2014.01.018.
[16] X. Li, J. Zhang, B. Fu, C. Song, W. Shang, P. Tao, T. Deng, Erythritol impregnated within surface-roughened hydrophilic metal foam for medium-temperature solar-thermal energy harvesting, Energy Convers. Manag. 222 (2020) 113241, https://doi.org/10.1016/j.enconman.2020.113241.
[17] R. Anish, V. Mariappan, M.M. Joybari, A.M. Abdulateef, Performance comparison of the thermal behavior of xylitol and erythritol in a double spiral coil latent heat storage system, Therm. Sci. Eng. Prog. 15 (2020) 100441, https://doi.org/10.1016/j.tsep.2019.100441.
[18] B. Feng, L.-W. Fan, Y. Zeng, J.-Y. Ding, X.-F. Shao, Atomistic insights into the effects of hydrogen bonds on the melting process and heat conduction of erythritol as a promising latent heat storage material, Int. J. Therm. Sci. 146 (2019) 106103, https://doi.org/10.1016/j.ijthermalsci.2019.106103.
[19] A. Chibani, A. Dehane, S. Merouani, O. Hamdaoui, Phase change material (PCM)-based thermal storage system for managing the sonochemical reactor heat: thermodynamic analysis of the liquid height impact, Ultrason Sonochem 98 (2023) 106483, https://doi.org/10.1016/j.ultsonch.2023.106483.
[20] A. Chibani, S. Merouani, A. Dehane, Heat management in sonochemical reactor using fins-PCM integrated system: unveiling the influence of the sonicated volume, J. Eng. Res. 12 (2024) 629–640, https://doi.org/10.1016/j.jer.2024.01.017.
[21] Y. Devarajan, Performance and emission analysis of sterculia foetida biodiesel enhanced with butanol: Combustion efficiency and emission mitigation, Results Eng. 25 (2025) 104586, https://doi.org/10.1016/j.rineng.2025.104586.
[22] A. Chibani, S. Merouani, H. Laidoudi, A. Dehane, C. Bougriou, Thermal management and electrical efficiency for concentrator photovoltaic systems using multiple phase change materials, App. Ther. Eng. 240 (2024) 122207, https://doi.org/10.1016/j.applthermaleng.2023.122207.
[23] G. Wang, G. Wei, C. Xu, X. Ju, Y. Yang, X. Du, Numerical simulation of effective thermal conductivity and pore-scale melting process of PCMs in foam metals, Appl. Therm. Eng. 147 (2019) 464–472, https://doi.org/10.1016/j.applthermaleng.2018.10.106.
[24] H.-Q. Jin, L.-W. Fan, M.-J. Liu, Z.-Q. Zhu, Z.-T. Yu, A pore-scale visualized study of melting heat transfer of a paraffin wax saturated in a copper foam: effects of the pore size, Int. J. Heat Mass Transf. 112 (2017) 39–44, https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.114.
[25] Yimin Xuan, Qiang Li, Heat transfer enhancement of nanofluids, Int. J. Heat and Fluid Flow. 21 (2000) 58–64, https://doi.org/10.1016/S0142-727X(99)00067-3.
[26] A Treatise on Electricity and Magnetism, Nature. 7 (1873) 478–480, https://doi.org/10.1038/007478a0.
[27] Z.-X. Gong, A.S. Mujumdar, Cyclic heat transfer in a novel storage unit of multiple phase change materials, Appl. Therm. Eng. 16 (1996) 807–815, https://doi.org/10.1016/1359-4311(95)00088-7.
[28] A.L. Owolabi, H.H. Al-Kayiem, A.T. Baheta, Nanoadditives induced enhancement of the thermal properties of paraffin-based nanocomposites for thermal energy storage, Sol. Energy 135 (2016) 644–653, https://doi.org/10.1016/j.solener.2016.06.008.