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Thermophysical and Thermal Charging Enhancement of PEG/Al_2O_3 Composites for Thermal Energy Storage (TES)

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Abstract

The transition to renewable energy continues to face challenges in balancing supply and demand. Thermal Energy Storage (TES) based on Phase Change Materials (PCM) offers a potential solution, with polyethylene glycol (PEG) providing high storage capacity but low thermal conductivity. This study focuses on enhancing the performance of PEG 6000 by incorporating aluminum oxide (Al_2O_3, 8 and 12 wt.%) and sodium dodecyl benzene sulfonate (SDBS) as a surfactant. X-ray Diffraction (XRD) confirmed that no new phases were formed, while Differential Scanning Calorimetry (DSC) recorded an increase in latent heat up to 224.6 J/g for PEG/Al_2O_3 12%. Thermal conductivity improved by more than 33.3%, and Thermogravimetric Analysis (TGA) verified enhanced thermal stability. Charging–discharging tests further demonstrated an extended average charging time with slight fluctuations during discharging. These findings highlight the promising potential of PEG/Al_2O_3 composites for TES applications in renewable energy systems.

Introduction

The global energy sector is undergoing a significant transition, characterized by a shift away from fossil fuels toward renewable energy sources such as wind, solar, and hydro, driven by global environmental concerns, rising fossil fuel costs, sustainability demands, and the urgency of energy security [1]. However, the mismatch between energy supply and demand in renewable energy systems remains a major global challenge. Therefore, affordable and efficient energy storage is crucial to balance this mismatch [2]. Thermal Energy Storage (TES) is an energy storage system that can absorb, store, and release heat. TES utilizes excess thermal energy during periods of high supply, such as during the day in solar power plants, and makes it available during periods of limited supply or high demand, thereby enhancing both energy efficiency and availability [3]. TES systems are classified into three categories: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and thermochemical energy storage (TCES). Among them, LHTES employs Phase Change Materials (PCMs) to store and release heat and has been extensively studied for its ability to harness abundant thermal energy from sources such as solar and waste heat via nearly isothermal phase transitions. Consequently, PCMs are regarded as promising energy storage materials due to their ability to repeatedly absorb and release latent heat [4][5].

Phase Change Materials (PCMs) are generally categorized into three main groups: organic, inorganic, and eutectic [6]. Among them, organic PCMs have attracted increasing attention due to their low cost, high heat storage capacity, suitable phase transition temperatures, and favorable physicochemical and thermal properties, including non-toxicity, non-corrosiveness, chemical stability, and good thermal reliability. However, these advantages come with limitations. Most organic PCMs have low thermal conductivity (TC), which slows charging and discharging rates. Therefore, improving TC is crucial to accelerate heat transfer and enhance the overall efficiency of energy storage and release [7][8]. Previous studies have attempted to improve the thermal conductivity and performance of PCMs by incorporating nanoparticles. For instance, the addition of 1 wt.% Cu, Ag, Al_2O_3, and MgO nanoparticles resulted in varying TC enhancements in polyethylene glycol (PEG). The improvements were approximately 2% for Al_2O_3 and MgO, 5.4% for Ag, and 11.16% for Cu. This indicates that the thermal conductivity of PEG is strongly influenced by the intrinsic conductivity of the dispersed nanoparticles [9]. Similarly, the addition of 10 wt.% ZnO into paraffin increased its thermal conductivity by 76.4%, although the specific heat decreased by 10.7%. This conductivity improvement, combined with improved liquid-phase properties, increased the PCM-side heat transfer coefficient by 96% in a shell-and-tube TES unit, demonstrating significant performance gains [10]. Comparable results were reported by S. Singh et al. (2022) [11], who investigated paraffin-based latent heat thermal energy storage (LHTES) systems incorporating Al_2O_3, MgO, and SiO_2 nanoparticles through both experimental and numerical approaches. Their findings revealed substantial increases in charging rates of 33.8%, 33.8%, and 41%, and in discharging rates of 19.6%, 25%, and 30% for Al_2O_3-, MgO-, and SiO_2-doped PCMs, respectively. On the other hand, nanoparticle stability plays a critical role in the thermal performance of composites. Due to their high surface energy, nanoparticles tend to agglomerate, making homogeneous dispersion within the PCM challenging and consequently reducing efficiency. To mitigate this issue, many studies have employed surfactants to maintain nanoparticles in a dispersed state, preventing sedimentation or agglomeration and thereby enhancing colloidal stability [12]. In the study by A. Ansu et al. (2021) [13], Al_2O_3 nanoparticles at 1–5 wt.% with SDBS improved thermal conductivity by approximately 52%, while slightly reducing the latent heat by 9.4%. After 1500 phase change cycles, the material exhibited negligible variation in thermal performance, confirming its long-term stability and reliability. Y. Bhutto et al. (2020) [14]. reported improved thermal performance of paraffin wax (PW) RT47 with the addition of 0.1 and 0.3 wt.% multi-walled carbon nanotubes (MWCNTs) modified by sodium dodecyl benzene sulfonate (SDBS) at a 1:1 ratio. The results showed that PW/MWCNT composites exhibited TC enhancements of 51.29% (0.1 wt.%) and 76.5% (0.3 wt.%). Fourier-transform infrared spectroscopy (FT-IR) confirmed no new chemical interactions, while thermogravimetric analysis (TGA) indicated stable thermal properties. Similarly, N. Zaimi et al. (2022) [15] demonstrated improved thermal performance of paraffin with the addition of 1–5 wt.% graphene nanoplatelets (GNPs) using SDBS (1:1) as a surfactant. The 5 wt.% GNP composition exhibited the best results, with enhancements of 43.2% in latent heat, 69.5% in specific heat, 73.45% in heat transfer rate, 64.13% in total heat storage, and a 25.94-fold increase in TC. Furthermore, PV module testing confirmed a temperature reduction of up to 44.2%, underscoring the effectiveness of SDBS in improving thermophysical properties and its potential as a cooling medium for photovoltaic systems

Organic PCMs, despite their favorable melting points and high latent heat capacities, suffer from intrinsically low thermal conductivity, which significantly limits their heat transfer efficiency and overall performance in Thermal Energy Storage (TES) systems. To overcome this limitation, the present study introduces a novel PEG 6000-based composite PCM by incorporating Al_2O_3 nanoparticles at 8 and 12 wt.% and employing sodium dodecyl benzene sulfonate (SDBS) as a surfactant to achieve a homogeneous and stable nanoparticle dispersion within the polymer matrix. This approach is expected to simultaneously enhance thermal conductivity while maintaining PEG 6000's latent heat storage capacity. Furthermore, the study systematically investigates the thermophysical characteristics and evaluates the charging–discharging behavior of the PEG/Al_2O_3 composites, thereby bridging the gap between material design and practical implementation for efficient TES applications.

Experimental Method

Polyethylene Glycol (PEG) with a molecular weight of 6000 and a melting point of 58–63 °C was obtained from Merck as the base material. Alumina (Al_2O_3) nanoparticles and Sodium Dodecyl Benzene Sulfonate (SDBS, purity >98%) surfactant were supplied by Sigma-Aldrich and used without further purification. Figure 1: Experimental workflow of PCM Composites. The study began with preliminary characterization of the constituent materials (PEG6000 and Al_2O_3) to determine their thermal and physical properties prior to composite fabrication. PEG/Al_2O_3 composites containing 8 and 12 wt% Al_2O_3 were prepared using a two-step method, following previous studies [16].

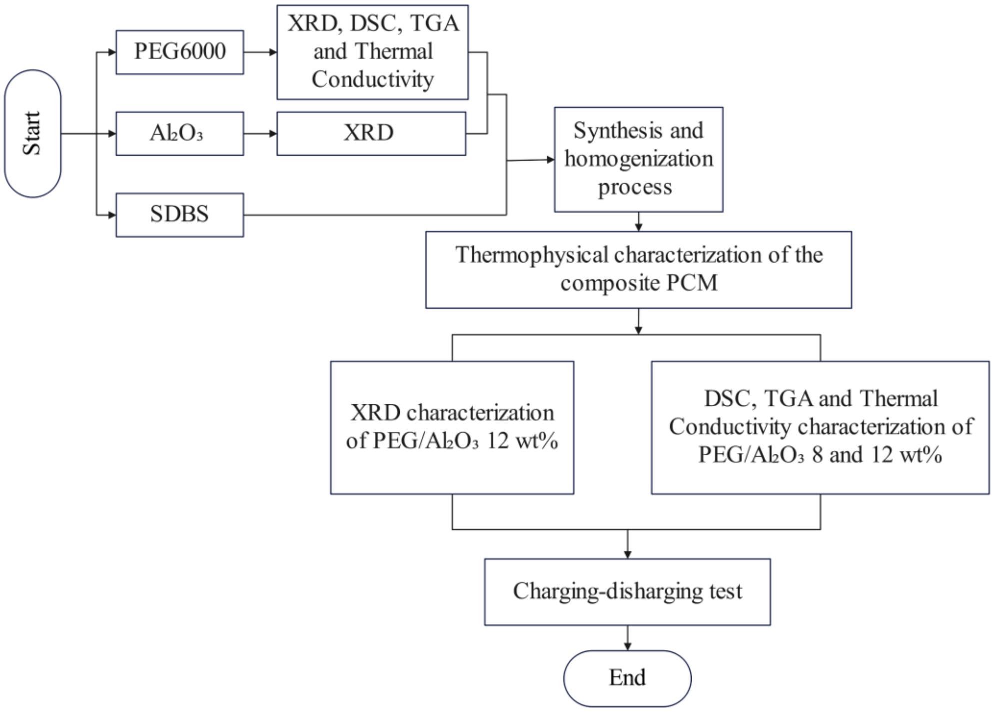


Figure 1. Experimental workflow of PCM Composites.

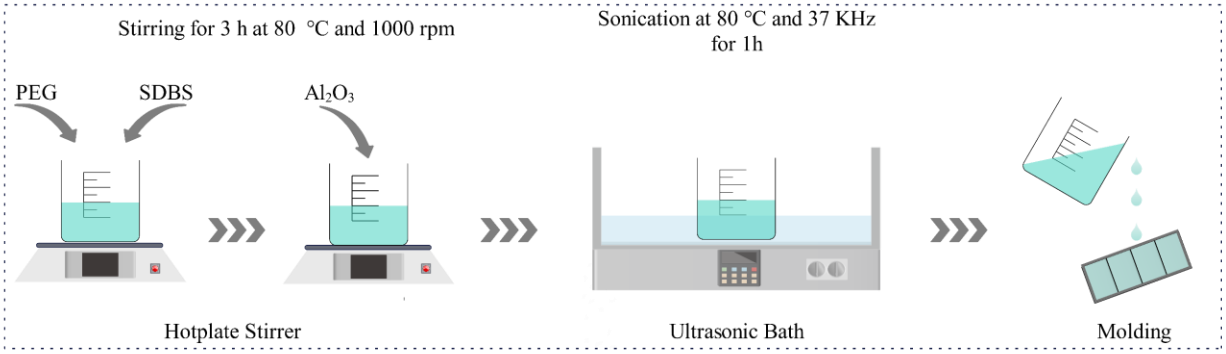


Figure 2. Synthesis of PEG/Al_2O_3.

In the first step, PEG was heated to 80 °C to achieve a homogeneous liquid state. SDBS was then added, and the mixture was stirred using a magnetic stirrer for 1 h at 1000 rpm. Subsequently, Al_2O_3 particles were incorporated, and stirring was continued for an additional 2 h under the same conditions. The resulting mixture was then sonicated at 80 °C and 37 kHz for 1 h to further enhance particle homogenization and dispersion. Meanwhile, SDBS was used at a mass ratio of 1:0.5 relative to Al_2O_3 to suppress agglomeration and improve particle wettability, thereby promoting more uniform distribution and enhancing the thermal properties of the composites. The overall synthesis process can be seen in Figure 2 [15]. Nevertheless, excessive surfactant may reduce thermal conductivity and induce the formation of air bubbles that are difficult to eliminate [17], [18]. The analysis and characterization of the PCM's thermophysical properties were carried out using various techniques. Crystal structure and phase characterization were performed by X-ray Diffraction (XRD, SMARTLAB RIGAKU, Cu Kα, $\lambda = 1.5418$ Å). Thermal properties were analyzed using

Differential Scanning Calorimetry (DSC, Polyma DSC 214) to determine latent heat, melting temperature, and freezing temperature at a heating/cooling rate of 10 °C/min within the range of 25–100 °C. Thermal stability was evaluated by Thermogravimetric Analysis (TGA, PerkinElmer TGA 4000) at a rate of 10 °C/min up to 600 °C. Meanwhile, thermal conductivity was measured using the hot-wire method with a QTM-500 instrument.

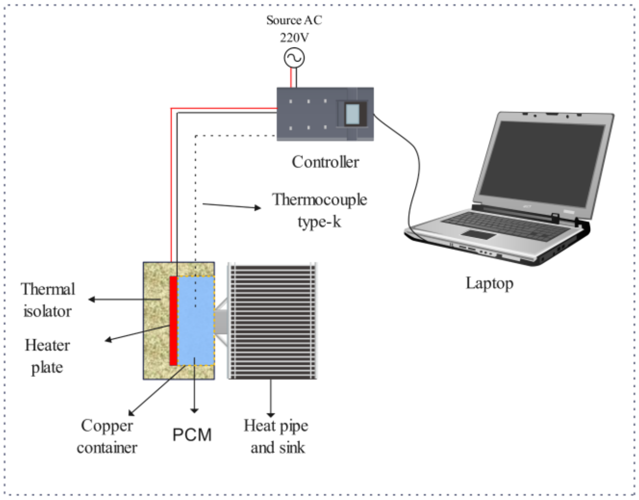


Figure 3. Experimental Setup of PEG/Al_2O_3 for Charging and Discharging.

The charging and discharging processes of PCMs are crucial factors in the application of Thermal Energy Storage (TES), as they largely determine the performance of PCMs when implemented in large-scale practical systems [19][20]. Therefore, in addition to analyzing the thermophysical properties of PEG/Al_2O_3 composites, this study also conducted simple charging–discharging performance tests on pure PEG and PEG/Al_2O_3 composites. Figure 3 illustrates the charging and discharging processes of PCM. The experiments were performed in a 3.5 mL copper container. A heater plate served as the heat source, while a passive cooling system used a heat pipe and a heat sink. The entire system was controlled by an Arduino microcontroller (ATmega 2560) with a type-K thermocouple as the temperature sensor. The test procedure was initiated by setting upper and lower temperature limits of 100 °C and 35 °C, respectively, and was operated for six charging–discharging cycles. Temperature data were then collected on a computer for further analysis of the PCM's charging and discharging performance.

Results and Discussion

X-Ray Diffraction

Figure 4 presents the XRD patterns of Al_2O_3, PEG6000, and PEG/Al_2O_3 (12 wt.%) composite. The diffractogram pattern of Al_2O_3 indicates the formation of a single phase consistent with reference data COD #96-120-0016, corresponding to η-Al_2O_3 [21][22]. .Three main peaks of Al_2O_3 were observed at 2θ values of 37.52°, 45.66°, and 67.06°. For pure PEG, characteristic crystalline peaks were detected at 2θ = 19.18° and 23.24°, confirming the crystalline domains within the polymer matrix [23][24][25]. In the PEG/Al_2O_3 (12 wt.%) composite, the XRD pattern demonstrated that the crystalline structure of pure PEG was preserved. The addition of Al_2O_3 nanoparticles did not induce significant changes in the crystalline configuration. This suggests that the interaction between PEG and Al_2O_3 is primarily physical rather than chemical. Furthermore, the absence of new peaks or secondary phases confirmed that Al_2O_3 is chemically compatible with PEG, enhancing material properties without adverse chemical reactions [26]. These results align with previous studies on PEG 10,000/Al_2O_3 composites, where PEG retained its original crystallinity and Al_2O_3 peaks were identified without the formation of new phases. These findings confirm that the PEG–Al_2O_3 interaction occurs through physical dispersion of nanoparticles in the polymer matrix rather than through chemical bonding [13]. A similar trend was observed for PEG 6000/Fe_3O_4 composites, in which no new diffraction peaks were detected, confirming successful synthesis and reinforcing the interaction as entirely physical, with no evidence of chemical reactions between components [23].

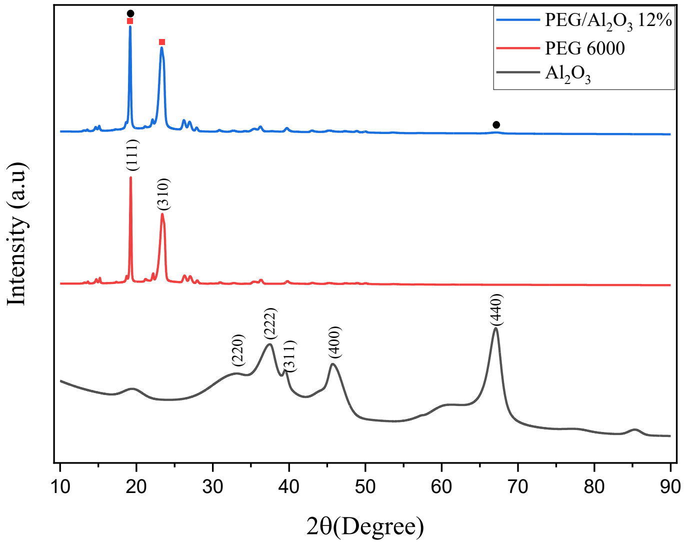
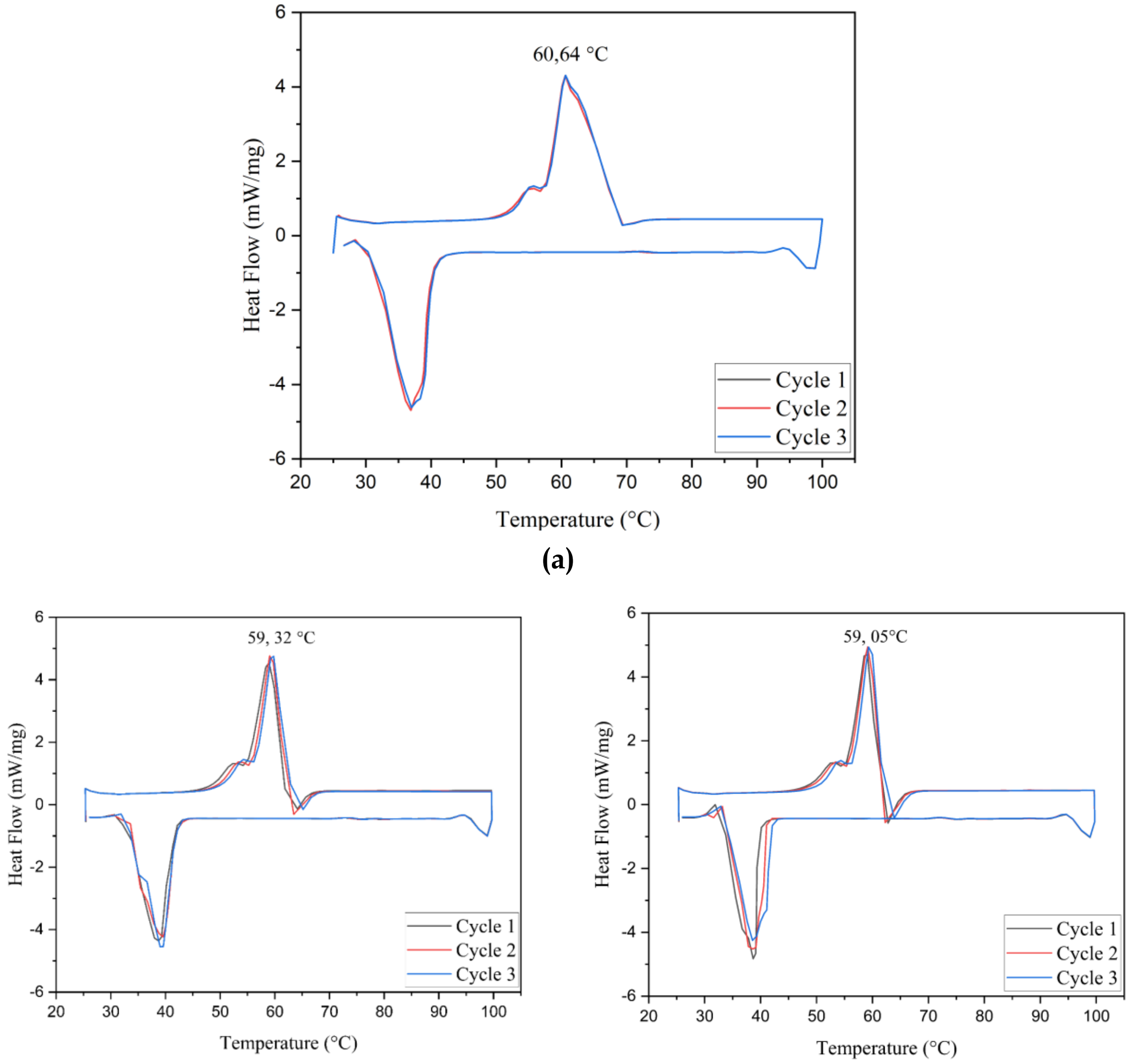


Figure 4. XRD analysis of Al_2O, PEG6000 and PEG/Al_2O_3 12%

Differential Scanning Calorimetry (DSC)

The ability of PCMs to store and release thermal energy as an energy storage medium is determined by their melting temperature or range, phase-change enthalpy, and heat capacity in both solid and liquid states [27]. Figure 5 (a–c) shows the Differential Scanning Calorimetry (DSC) curves of pure PEG and PEG/Al_2O_3 composites. Pure PEG exhibited a melting temperature of 60.64 °C. A slight reduction in melting temperature was observed with the addition of Al_2O_3, with the largest decrease found in the PEG/Al_2O_3 (12 wt.%) composite, at 59.05 °C. This trend is consistent with previous studies showing that adding Al_2O_3 to paraffin slightly reduces the melting temperature; the melting temperatures were 33.8, 33.63, and 32.26 °C for mass fractions of 0%, 4%, and 11%, [28]. Similar effects were also reported for BN/ZnO nanoparticles, which enhanced thermal conductivity, accelerated heat transfer, lowered the melting temperature, and provided nucleation sites to suppress supercooling [26]. Overall, the small melting temperature shift in nanoparticle-enhanced PCMs arises from changes in interfacial interactions between the PCM and the nanoparticles, which can modify molecular ordering during the phase transition [20].



(a)

(b) **(c)**

Figure 5. Results of the Differential Scanning Calorimetry (DSC) analysis. (a) PEG6000 (b) PEG/Al_2O_3 8% (c) PEG/ Al_2O_3 12%.

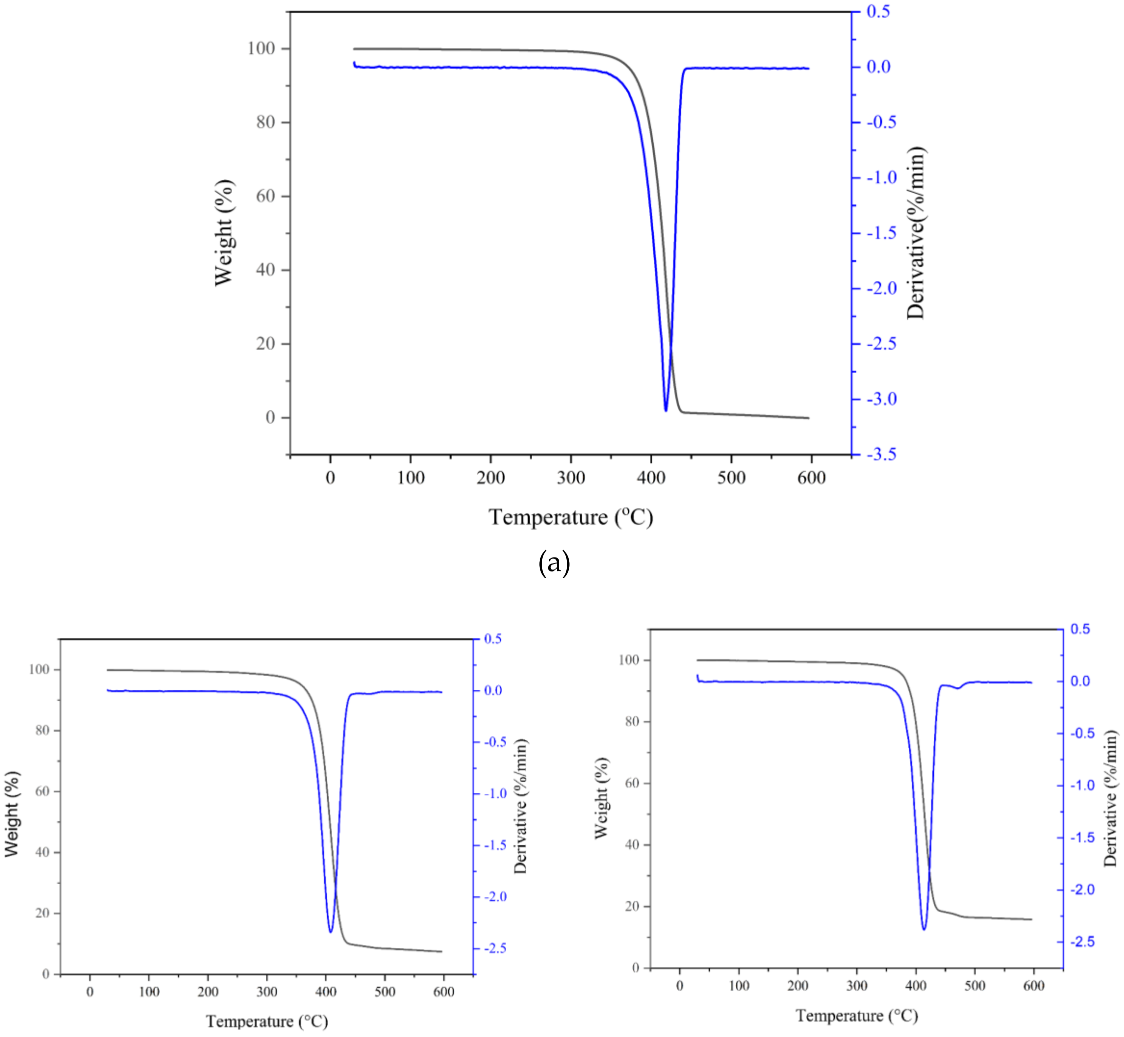
Meanwhile, pure PEG showed a latent heat value of 212.45 J/g. The addition of 8 and 12 wt.% Al_2O_3 altered the latent heat to 217 J/g and 222.46 J/g, respectively. The increase in latent heat is attributed to the use of sodium dodecyl benzene sulfonate (SDBS) as a surfactant, which promoted uniform particle dispersion by modifying particle surfaces via electrostatic repulsion. Furthermore, SDBS provided a physical barrier between particles, minimizing agglomeration typically caused by van der Waals forces [29][30]. In earlier studies, the addition of ZnO with SDBS as a surfactant enhanced the latent heat of PEG by 11.4% and 20.4%, respectively. The increased ZnO content with larger surface area strengthened particle interactions and facilitated faster heat transfer, thereby accelerating melting and optimizing energy absorption and latent heat capacity, particularly at higher nanoparticle mass fractions. A similar trend was also reported by M. Mohan et al. (2025) [31], who incorporated 5 wt.% CuO with SPAN-80 surfactant into paraffin. Their results demonstrated a 48.5% improvement in thermal conductivity, accompanied by an increase in latent heat of 29.1% during melting and 15.6% during solidification compared to pure paraffin.

Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) was employed to evaluate the thermal stability of pure PEG and PEG/Al_2O_3 composites (8 and 12 wt.%). Figure 6(a–b) shows that all samples underwent a single-step decomposition within the temperature range of 20–600 °C. Pure PEG began to decompose at 375.5 °C. Differential Thermogravimetric (DTG) analysis revealed a decomposition peak at 417.88 °C, with a maximum mass loss rate of 3.09%/min. According to previous studies, at approximately 430 °C, the PEG polymer chains are completely degraded into monomers, as illustrated in Figure 6a [13][32]. Figures 6(b–c) present the TGA results of the PEG composites. The PEG/Al_2O_3 (8 wt.%) sample started to decompose at 365.29 °C, with a decomposition peak at 408 °C and a maximum mass loss rate of 2.30%/min. Meanwhile, PEG/Al_2O_3 (12 wt.%) began to decompose at 374.5 °C, with a decomposition peak at 413.64 °C and a maximum mass loss rate of 2.40%/min. Both PEG composites exhibited initial decomposition temperatures significantly higher than the working temperature range of PEG (50–60 °C), indicating that PEG/Al_2O_3 (8 and 12 wt.%) possessed excellent thermal stability. On the other hand, the initial and peak decomposition temperatures of PEG/Al_2O_3 were slightly lower compared to pure PEG. These findings are consistent with previous reports, in which the initial decomposition temperature of PEG/Modified Fly Ash (MFA) decreased by 50.6 °C, and the temperature corresponding to the maximum weight-loss rate decreased by 19.9 °C compared to pure PEG. The incorporation of MFA acted as a thermal conductivity bridge and provided efficient permeation pathways for heat flow, significantly improving the thermal conductivity of PEG/MFA and enhancing its heat transfer performance during evaporation [33].

PCMs with higher thermal conductivity require shorter charging and discharging times, which directly affects the efficiency of thermal energy storage systems [34]. The reversible storage and release of thermal energy in PCMs primarily occur through the transition between ordered and disordered molecular structures. In general, thermal conduction in solids can be classified into three mechanisms: electronic, phonon, and photon conduction. These mechanisms are associated with different carriers—free electrons, lattice vibrations, and electromagnetic radiation, respectively. Among them, photon conduction contributes only marginally in most materials, making electronic and phonon conduction the dominant mechanisms of heat transfer [35]. Thermal conductivity plays a crucial role in thermal energy storage systems, as it reflects the rate at which heat is transferred across the material. A higher thermal conductivity enhances heat transfer, thereby improving the overall system efficiency [36]. Figure 7 shows that incorporating Al_2O_3 particles into PEG enhances its thermal conductivity; pure PEG has a thermal conductivity of 0.3 W/m ·K. These findings are consistent with results reported in previous studies [32][37].

Meanwhile, the thermal conductivity values for additions of 8 and 12 wt.% Al_2O_3 were 0.38 and 0.40 W/m ·K, respectively.



(a)

(b)

(c)

Figure 6. TGA and DTG analysis of (a) PEG6000 (b) PEG/Al_2O_3 8% (c) PEG/ Al_2O_3 12%.

This indicates that incorporating Al_2O_3 successfully enhances thermal conductivity, with the values increasing proportionally to the Al_2O_3 concentration. Specifically, the addition of 8 and 12 wt.% Al_2O_3 significantly improved thermal conductivity by 26.67% and 33.33%, respectively. Similar enhancements in thermal conductivity following Al_2O_3 incorporation have also been reported in previous studies [38][39][40].

Charging and Discharging PCM

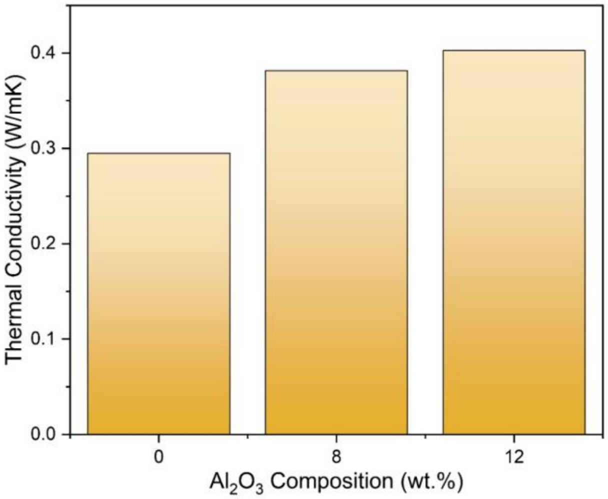
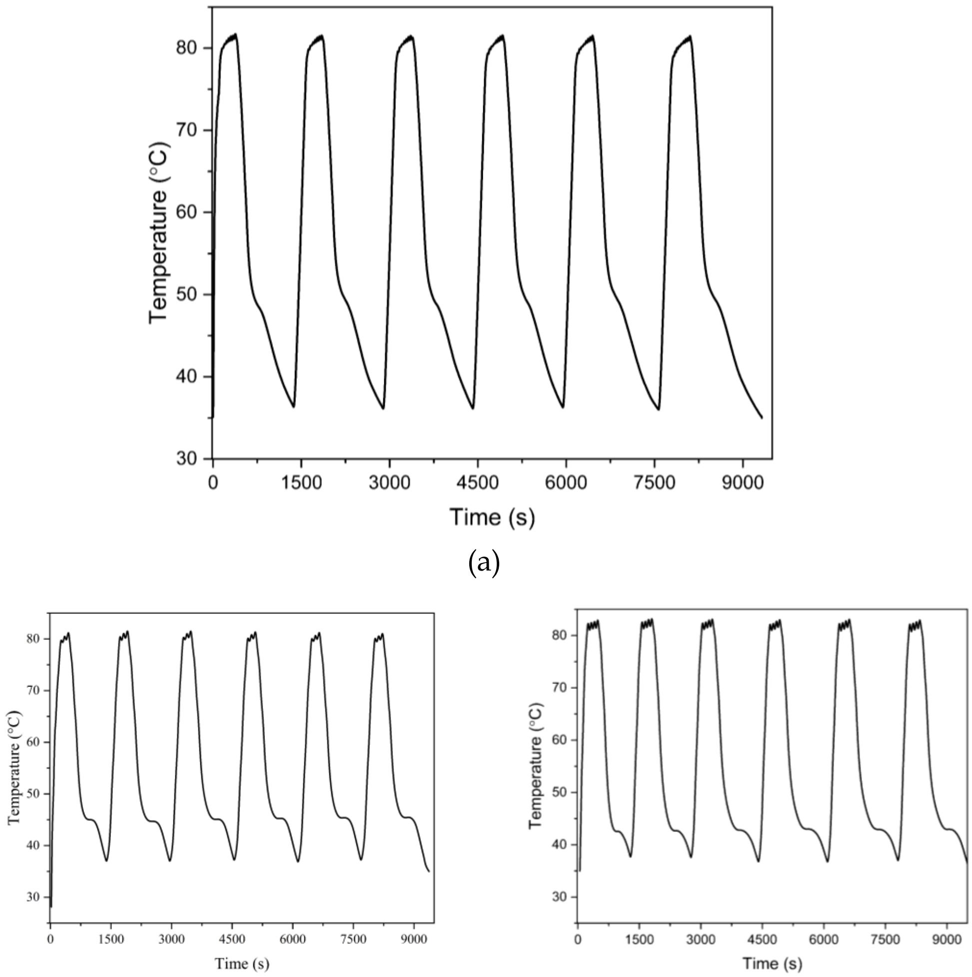


Figure 7. Thermal conductivity of PEG6000, PEG/Al_2O_3 8%, and PEG/Al_2O_3 12%.

Figure 8(a–c) illustrates the charging and discharging processes of pure PEG and PEG/Al_2O_3 composites (8 and 12 wt.%). The tests began with charging, where the samples were heated from 35 to 80 °C. Pure PEG required an average charging time of 485.4 s over six cycles, whereas PEG/Al_2O_3 (8 wt.%) and PEG/Al_2O_3 (12 wt.%) required 319.33 s and 257.16 s, respectively. This corresponds to reductions of 34.3% and 47.0% compared to pure PEG. Similar results were reported in previous studies, where the addition of 0.5–6% unzipped multiwalled carbon nanotube oxides (UMCNOs) to PEG reduced the charging time by 9.92–40.02%, due to the formation of interconnected networks within the PEG matrix that shortened phonon transport pathways and accelerated heat transfer [41]. Likewise, incorporating Al_2O_3, CuO, TiO_2, and ZnO nanoparticles into PEG reduced melting times by 20%, 15%, 6%, and 3%, respectively, compared to pure PEG. This improvement was primarily attributed to enhanced thermal conductivity, although the order of melting time reduction did not fully match the order of conductivity enhancement [40]. During discharging, pure PEG required an average of 1298 s. For PEG/Al_2O_3 (8 wt.%), the average discharging time decreased to 1242.5 s, while PEG/Al_2O_3 (12 wt.%) showed a slight increase to 1321.33 s. The longer discharge time in PEG/Al_2O_3 (12 wt.%) is associated with its higher latent heat, which requires more time for heat release. Overall, the PEG/Al_2O_3 composites improved the thermal performance of PCM during both charging and discharging, demonstrating their promising potential for practical application in thermal energy storage (TES) systems.



(a)

(b)

(c)

Figure 8. Charging and discharging of (a) PEG6000 (b) PEG/Al_2O_3 8% (c) PEG/Al_2O_3 12%.

Conclusion

In this study, the thermal performance of PEG 6000-based organic PCM was enhanced by incorporating Al_2O_3 nanoparticles (8 and 12 wt.%) and employing sodium dodecyl benzene sulfonate (SDBS) as a surfactant to achieve a homogeneous dispersion of Al_2O_3 within the PEG matrix. The PEG/Al_2O_3 composites were successfully synthesized, demonstrating improved thermophysical properties and superior thermal performance. This improvement was evident when compared to pure PEG, which exhibited a latent heat of 212.45 J/g. The addition of 8 and 12 wt.% Al_2O_3 altered the latent heat values to 217 J/g and 222.46 J/g, respectively. Consistently, the incorporation of Al_2O_3 enhanced the thermal conductivity by 26.67% and 33.33%. Thermal stability analysis revealed that both PEG/Al_2O_3 composites exhibited initial decomposition temperatures well above the operational range of PEG (50–60 °C), confirming their excellent thermal stability. However, compared to pure PEG, the initial and peak decomposition temperatures of the composites were slightly reduced. XRD analysis further indicated that the crystalline structure of pure PEG remained intact, with the addition of Al_2O_3

nanoparticles causing no significant alteration to its crystal configuration. The charging time decreased from 485.4 s (pure PEG) to 319.33 s and 257.16 s for 8 wt.% and 12 wt.% Al_2O_3, representing reductions of 34.3% and 47.0%, respectively. During discharging, the 8 wt.% composite slightly accelerated heat release, while the 12 wt.% composite required longer due to its higher latent heat. Overall, the incorporation of Al_2O_3 (8 and 12 wt.%) significantly improved the thermophysical properties and the charging and discharging behavior of PEG. Therefore, PEG/Al_2O_3 composites show strong potential as promising PCM candidates for Thermal Energy Storage (TES) systems, particularly in supporting the transition to clean, renewable energy technologies.

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