

Thermal energy storage behaviour of form-stable polyethylene glycol/MWCNT- based phase change materials

*Aman Yadav*¹, *M. Samykano*^{1*}, *A. K Pandey*^{2,3*}, *B. Kalidasan*², *R. Reji Kumar*^{4,5}, *K. Kadirgama*¹, *A. G. N. Sofiah*⁴, and *W. K. Ngui*¹

¹Faculty of Mechanical & Automotive Engineering Technology, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

²Research Centre for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No. 5, Jalan Universiti, Bandar Sunway, Petaling Jaya 47500, Selangor Darul Ehsan, Malaysia

³Center for Transdisciplinary Research (CFTR), Saveetha Institute of Medical and Technical Science, Saveetha University, Chennai, India

⁴Institute of Sustainable Energy, Universiti Tenaga Nasional (@The National Energy University), Jalan IKRAM-UNITEN, Kajang, Selangor, Malaysia

⁵Institute of Sustainable Energy, Universiti Tenaga Nasional (National Energy University), Jalan IKRAM-UNITEN, Kajang, Selangor, Malaysia. 2Division of Research and Development, Lovely Professional University, Phagwara, Punjab, 144411, India.

Abstract: Organic phase change materials (OPCMs) possess a remarkable ability to absorb and release latent heat during phase transitions, making them very promising for storing solar energy. Nevertheless, the extensive use of these materials encounters substantial obstacles arising from intrinsic difficulties, such as limited heat conductivity and chemical stability concerns. The authors of this innovative work have successfully led the way in developing a state-of-the-art nano-enhanced organic phase change material (Ne-OPCM). This novel substance utilizes polyethylene glycol (PEG) as the primary phase transition material, which is smoothly incorporated into a network of polymethyl methacrylate (PMMA) to reduce obstacles caused by molecular size and improve chemical durability. In order to overcome the issue of poor thermal conductivity, the researchers selectively used multi-walled carbon nanotubes (MWCNT) as a conductive filler. This resulted in a significant increase in the thermal conductivity of PEG-1000. In an ongoing study, thermal characteristics of the developed (Ne-OPCM) composites are evaluated for different weight fractions of 0.3 %, 0.7 %, and 1.0 % of MWCNT. In addition to the morphology, thermal property, chemical stability, optical absorptivity and the latent heat of the developed PEG-PMMA/MWCNT (Ne-OPCM) composite are evaluated using FESEM, FT-IR, UV-Vis spectroscopy TGA and DSC instruments. The thermal conductivity of PEG-PMMA/MWCNT (Ne-OPCM) composite was improved by 87.64 % with a dispersion of 0.7 wt% of MWCNT. The DSC conducted highest latent heat and melting point of a PEG-PMMA/MWCNT (NePCM) composite are 139.66 J/g & 40.4 °C occurring at 0.7 wt% of MWCNT. Consequently, the developed (Ne-OPCM)

* Corresponding author: mahendran@ump.edu.my; adarsh.889@gmail.com

composites have promising potential in practical solar energy storage applications at the temperature range of 35-40 °C.

Keywords: Polyethylene glycol; polymethyl methacrylate; thermal energy storage; chemical stability; steric hindrance.

1 Introduction

In current ages, renewable and sustainable energies have been essential in the energy crisis since the 1970s. TES arrangements offer the probable possibilities to accomplish energy reserves, which diminish the environmental effect associated with energy usage; these arrangements essentially deliver an appreciated resolution for amending the misalliance regularly found amongst energy supply and demand [1]. Storing latent heat is the best well-organized behaviour for TES. The latent heat storage approach provides a larger storage capacity with just small temperature variations between storing and releasing heat, in contrast to sensible heat storage method. Organic PCMs are premeditated as an excellent choice for TES [2]. Organic PCMs possess a significant thermal energy storage capacity as a result of their increased heat of fusion. These properties make them well-suited for a range of uses, including regulating temperature in buildings, powering solar energy systems, and creating fabrics that provide thermal comfort. PCMs efficiently transmit thermal energy during phase change from solid to liquid or vice versa because of the constant temperature at which they store energy. The two mutually exclusive PCM assemblies are organic and inorganic PCMs [3]. Paraffin and non-paraffin organic PCMs are the two categories. Significant organic-PCM qualities include thermal stability and non-corrosivity. No supercooling is well-matched for TES at low vapour pressure and high latent heat per unit weight. However, organic PCMs have a low thermal conductivity restriction. Also, as a phase transitions, a liquid phase generates difficulties like chemical stability [4], high fluctuations in volume on flammability, and phase change [5]. However, broad research was conducted to improve heat transfer rate [6].

In the current study, a main objective of research is to improve the chemical stability and thermal conductivity of OPCMs with the help of various nanoparticles and supporting materials. Various research is done on enhancing thermal conductivity and chemical stability with the help of nanoparticles, and supporting materials are discussed in detail. Zang et al. [7] performed an experimental analysis of thermal characteristics of a SSPCM. This material consisted of PEG-6000 as PCM, cellulose as a supporting substance, and GNPs as nanoparticles. Results indicated that thermal conductivity of SSPCM was 0.44 W/m·K, which exhibited an enhancement compared to pure PEG. This work utilized carbon-based GNPs to augment the thermal conductivity of the composite material. The high thermal conductivity of GNPs significantly reduced the thermal resistance between PEG and GNP particles. Moreover, the specific heat capacity and temperature at which SSPCM transitions from solid to liquid were measured to be 156.2 J/g and 63 °C, respectively, both of which are lower than base PCM. A decrease in latent heat can be ascribed to a drop in weight % resulting from the presence of GNP particles, as well as interference in the crystallization process of PEG. These findings demonstrate that the addition of carbon-based GNPs has a beneficial effect on increasing thermal conductivity in the composite. However, it is important to note that this also leads to changes in latent heat and melting point. Jing et al. [8] conducted pioneering research where they performed new experiments to investigate the thermophysical characteristics of composites made up of PEG-2000 and GF. The results showed a significant increase in the thermal conductivity of the SSPCM, reaching an

astonishing value of 0.351 W/m·K, which is higher than that of pure PEG. In order to enhance the thermal performance of the composite material, the deliberate addition of CNT nanoparticles was used. The objective was to reduce heat resistance between PEG and graphene particles by using the remarkable thermal conductivity of CNTs. The use of CNTs resulted in significant improvements in the connectivity of the composite material. The SSPCM had a latent heat capacity of 68.64 J/g, along with a melting temperature of 48.41 °C, which are somewhat lower than the values seen in pure PEG. The decrease in latent heat was ascribed to the complex interaction between GF and PEG/CNT, resulting in the creation of weak van der Waals forces aided by the increased porosity of the composite. Surprisingly, this interaction caused a reduction in latent heat while simultaneously boosting the overall thermal properties of the composite material to new levels. In a groundbreaking study conducted by Zheng et al. [9], the thermal properties of innovative NePCM composites were meticulously explored. The study utilized the vacuum impregnation technique to create NePCMs, using PEG-10000 as the PCM, MCNT as nanoparticles, and CPC as a vital supporting material. The composite demonstrated exceptional thermal conductivity, achieving an outstanding value of 0.494 W/m·K. This represented an astonishing 230 % surge in comparison to the thermal conductivity of the underlying PCM. The significant improvement in heat conductivity is mainly due to the outstanding thermal conductive characteristics of the nanoparticles that have been added. This novel method not only demonstrates the potential for substantial progress in thermal management but also emphasizes the crucial role of nanotechnology in pushing the limits of material science. In the study conducted by Chen et al. [10], a thorough investigation was carried out on the thermal characteristics of composites, including PCM. The specific areas of interest were thermal conductivity, melting point, and latent heat. The composite, consisting of lauric acid as the PCM and activated carbon as the supporting material, had an impressive thermal conductivity of 0.308 W/m·K. This figure demonstrates a remarkable 92.5 % enhancement in comparison to pure PCM, highlighting the efficacy of activated carbon in improving the thermal efficiency of the composite. The deliberate inclusion of activated carbon in the composite was crucial in enhancing thermal conductivity by reducing the thermal resistance between the base PCM and the particles of the supporting material. This underscores not only the need to choose the right materials but also the possibility of customizing improvements in thermal qualities through careful composite design. In addition, the study found that the PCM composite had lower values for latent heat (65.14 J/g) and melting point (44.07 °C) compared to the basic PCM. The nuanced result was ascribed to the intentional decrease in weight % of activated carbon particles, which subsequently alleviated interference with the crystallization process of the basic phase change material (PCM). Their rigorous control shows the researchers' comprehensive grasp of the interplay between components over composite composition. This paves the path for revolutionary breakthroughs in thermal energy storage materials. Jing et al. [11] conducted pioneering experiments to study the thermal properties of a composite material that includes a PCM. The chosen PCM, n-octadecane, was improved by using activated carbon particles as support materials. The results demonstrated a significant increase in thermal conductivity, reaching 0.168 W/m·K, compared to the initial PCM. The incorporation of activated carbon particles was crucial in enhancing thermal conductivity by reducing thermal resistance between the base PCM and the particles of the supporting material. Furthermore, the SSPCM possesses distinct attributes such as a latent heat capacity of 101.8 J/g and a melting temperature of 32.8 °C. Significantly, these values were somewhat lower than the ones recorded for pure PEG. The decrease in latent heat was ascribed to the development of subtle van der Waals contacts between the composite and activated carbon, prompted by the latter's significant porosity.

The present work aims to fill a significant need in the current body of research by specifically examining the improvement of thermal characteristics in composites made of

PEG-PMMA and MWCNT. Prior studies have employed various supporting materials, such as metal foam [12], attapulgite [13], expanded perlite [14] and graphene sponges [15] and graphene sponges [16] to enhance the thermal properties of phase change materials. These accompanying materials frequently exhibit complex structures, permeable networks, and extensive surface areas. Their responsibility includes enhancing thermal efficiency rates of dispersion [17] and guaranteeing the homogeneous distribution of nanoparticles inside PCM composites [18]. PMMA was selected as the supporting material for our inquiry because of its exceptional characteristics, such as a porous structure and chemical stability. These traits are advantageous in reducing steric hindrance [19] and resolving the thermal stability [20] problems associated with PEG-1000 [21]. Concurrently, MWCNT nanoparticles were added to increase the thermal conductivity of PEG-PMMA. The use of MWCNT as a nanofiller is justified due to its one-dimensional structure, which exhibits excellent thermal conductivity and effective adsorption capabilities with organic PCMs. The basic PCM, PEG-1000, is characterized by its non-corrosive, non-flammable [22], and chemically stable properties. PEG-1000, with a melting point of 37 °C and a notable latent heat of 145 J/g, is an excellent choice for waste heat storage applications. The chemical stability of the substance is much improved due to its molecular weight of around 1000, which allows for smooth interaction with both PMMA and MWCNT. This intentional molecular design enhances its adaptability for high-performance applications and also creates opportunities for innovative research in the field of waste heat management. The intrinsic ability of PEG-1000 to make strong connections with PMMA and MWCNT highlights its potential as a revolutionary component in advanced research projects, offering creative solutions in the area. The NePCM, which combines PEG-1000, PMMA, and MWCNT, demonstrates a significant enhancement of 92.30 % in thermal conductivity, reaching an ideal value of 0.501 W/mK, exceeding the base PEG-PMMA's 0.267 W/mK. This improvement highlights the effectiveness of this distinct combination in enhancing thermal characteristics. In addition, the novel NePCM exhibits a notable 7.93 % augmentation in latent heat in comparison to the basic PEG-PMMA. Hence, this first NePCM has remarkable capability and effectiveness in retaining heat, offering potential for future applications in medium-temperature energy storage and the recovery of waste heat.

2 Materials

The polyethylene glycol used in this study was obtained from EDM Millipore Corporation in Darmstadt, Germany. It is reported to have a melting temperature range of 34 °C to 41 °C. PMMA used in this study was obtained from Sigma-Aldrich, a company based in Selangor, Malaysia. It was used in its original state without undergoing any further purifying processes. MWCNT nanoparticles, which played a major role in the experimental setup, were obtained from Hengquiu Tech: Inc, a famous Chinese firm. It is important to mention that no further purifying procedures were carried out on the PMMA. The exact thermal properties of the materials used are comprehensively presented in Table 1, offering critical insights into their thermal behaviour, which is crucial for this innovative research. A thorough knowledge of the experimental materials is achieved by considering the melting temperature of polyethylene glycol, the origin of PMMA, and the source of MWCNT nanoparticles. The incorporation of such varied components in the investigation not only demonstrates a purposeful selection procedure but also emphasizes the international cooperation involved in acquiring these resources from distinct areas, including Germany, Malaysia, and China. The carefully chosen assortment of materials serves as a basis for the following examinations and discoveries in the research, as clarified by the thermal properties provided in Table 1.

Table 1. The current study utilizes the key specifications of the materials as provided by the manufacturers.

Properties	Supporting materials	PCM	Nanoparticles
	PMMA	PEG-1000	MWCNT
Melting Point (°C)	142	37	3126
Heat of Fusion (KJ/Kg)	125-135	148	650
Thermal Conductivity (W/mK)	0.15-0.25	0.27	2585
Specific Heat (KJ/Kg.K)	1.470	2.142	0.7- 1
Density (Kg/m ³)	1165	1095	2165
Purity (%)	-	-	>95
Particle size (nm)	-	-	10-20
Color	White	White	Black

2.1 Preparation of (Ne-OPCM) composites

The technique of creating (Ne-OPCM) composites via ultrasonication is depicted in Fig. 1, with the preparation procedure outlined as follows. At first, the exact quantities of PEG-1000, PMMA, and 0.3 wt%, 0.7 wt%, and 1 wt% of MWCNT nanoparticles were determined using (EX224, OHAUS) an analytical microbalance. The PCM component, consisting of 90 % by weight, was heated at 80 °C using (RCT, BASIC IKA) a hot plate. After complete melting of PEG-1000, a determined quantity (10 wt%) of PMMA was added to the liquid PEG-1000. Following that, the PEG-PMMA solution attained full transparency, subsequently incorporating 0.3 wt% of MWCNT nanoparticles into the solution. The PEG-PMMA/MWCNT combination was subjected to ultrasonication using (EASY 60H, ELMASONIC), a water bath sonicator, for 1.5 hours at a temperature of 80 °C in last stage. The outcome was the achievement of consistently black and uniform mixtures following the process of sonication, which indicates the successful creation of the PEG-PMMA/(0.3)MWCNT (Ne-OPCM) composite. The same procedure was then replicated for the PCM composite, which consist of 0.7 wt% and 1.0 wt% MWCNT nanoparticles, respectively.

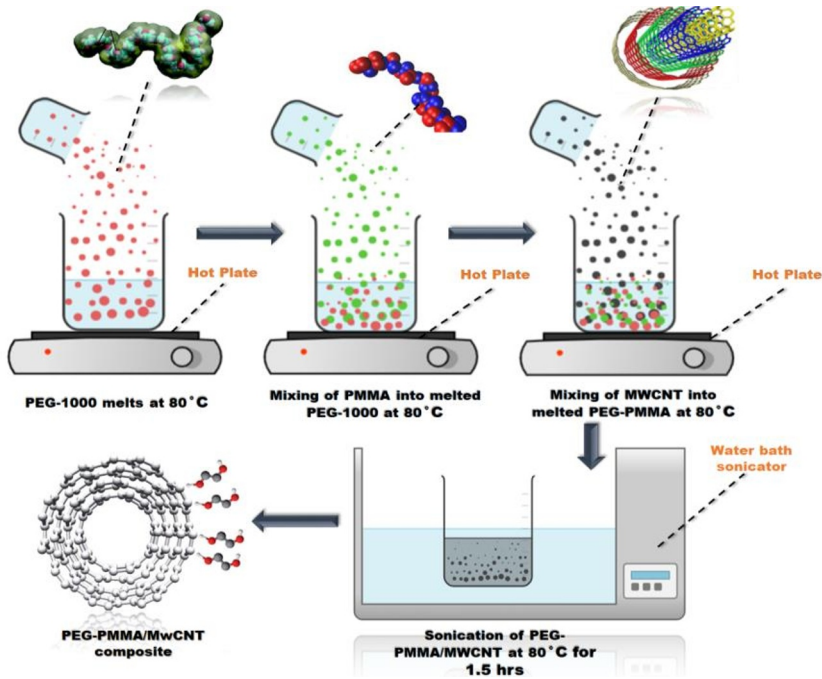


Fig. 1. The schematic preparation of PEG-PMMA/MWCNT (Ne-OPCM) composite.

2.2 Characteristics of the (Ne-OPCM) Composites

Several thermal-sensitive instruments examined the established (Ne-OPCM) composite's thermal, chemical, and light transmission characteristics.

2.2.1 Chemical characterization

The shape and size distribution of the PEG-PMMA/MWCNT (NePCM) composites were examined using Field Emission Scanning Electron Microscopy (FESEM) using a JBM-780 model. A state-of-the-art PERKIN ELMER FTIR Spectrum Two model was used to study Ne-OPCM chemical structures. Precision at 0.01 cm^{-1} and spectral resolution of 0.01 cm^{-1} were achieved over the 400 cm^{-1} to 4000 cm^{-1} wave number range. This complex method revealed functional groups, pollutants, and the material's chemical makeup. The optical absorptivity and transmissivity of Ne-OPCM were rigorously examined using UV-Vis spectroscopy on the cutting-edge LAMBDA 750 model by PERKIN ELMER, USA. The studies were methodically completed at ambient temperature and covered 200–1400 nm. These sophisticated analytical methods revealed the physical structure and chemical makeup of the (PEG-PMMA/MWCNT) composites, resulting in a high-impact research article with several interrelated findings.

2.2.2 Thermal characterization

The thermal diffusivity and conductivity of the Ne-OPCM composite were measured at room temperature using a thermal property analyzer (Tempos: dual needle SH-3). The thermal stability of (Ne-OPCM) composites was analyzed using a thermogravimetric analyzer (TGA: TGA-4000 Perkin Elmer) at $600\text{ }^{\circ}\text{C}$ and $5\text{ }^{\circ}\text{C}/\text{min}$. The melting point and latent heat of

NePCM composites are examined using DSC (3500 Sirius, NETZSCH). Under N₂, DSC is played at 5 °C to 55 °C at 5 °C/min chilling and heating.

3 Results and discussion

3.1 FESEM of (Ne-OPCM) composites

FESEM analyzed PEG-PMMA/MWCNT (NePCM) to determine their particle size and shape. Here, to enhance their thermal conductivity, MWCNT nanoparticles have been distributed in the base (PEG-PMMA) PCM. This study employs magnifications of 10X and 20X to obtain images of MWCNTs, PEG-1000, and a PEG-PMMA/MWCNT (NePCM) composite. The shape of MWCNT nanoparticles is shown in Fig. 2(a) and (b), where a rod-like structure of MWCNT was visible, consistent with what is described in literature [23]. PEG-PMMA morphology observed in Fig. 2(c) and (d) demonstrates a smooth surface-like structure described in the literature. The morphology of the PEG-PMMA/MWCNT composite is shown in Fig. 2(e). In conclusion, the MWCNT displayed a rod-like structure marked by red-dotted circles. Therefore, MWCNT was uniformly dispersed in the PEG-PMMA base and generated strong intermolecular interactions with the PEG-PMMA [24]. Moreover, the FESEM examination of PEG-PMMA/MWCNT (NePCM) composite demonstrates the effective incorporation of MWCNT nanoparticles into PEG-PMMA matrix, as shown by the presence of rod-shaped structures (Fig 2e). The even distribution of MWCNTs suggests that there are strong intermolecular interactions between the MWCNTs and the PEG-PMMA matrix. This leads to an improvement in thermal conductivity. Additionally, result verifies previously reported smooth surface morphology of PEG-PMMA and validates the rod-like structure of MWCNTs, which is consistent with the findings in current research. The results highlight the potential of the proposed PEG-PMMA/MWCNT composite for advanced thermal management applications, providing a promising opportunity to enhance heat transfer capabilities in PCMs.

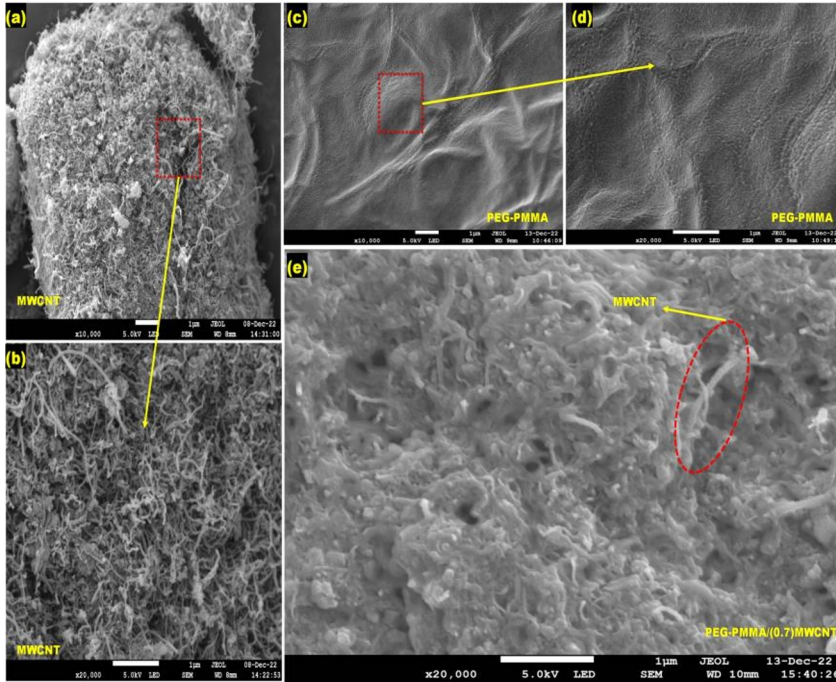


Fig. 2. FESEM morphology of a newly synthesized Ne-OPCM composite with MWCNT and a base PEG-PMMA (PCM).

3.2 Chemical nature analysis (FT-IR) of (Ne-OPCM) composites

A chemical composition of PCM composites was analyzed using an FTIR spectrometer in the present work, as shown in Fig. 3. The FTIR spectrum graph demonstrates the even distribution of MWCNT nanoparticles within base PCM (PEG-PMMA). Herein, nine main peaks were detected in base (PEG-PMMA) PCM, indicating notable molecular movements. The peak at 763 cm^{-1} shows significant mobility of $-\text{CH}_2$ groups [25], whereas a crystallization band ranging from 950 cm^{-1} to 1240 cm^{-1} suggests solidification. Distinct peaks were detected at wavenumbers of 1145 cm^{-1} , 1248 cm^{-1} , 1297 cm^{-1} , 1280 cm^{-1} , 1453 cm^{-1} , 2885 cm^{-1} , and 3426 cm^{-1} . The peaks at 1145 cm^{-1} and 1248 cm^{-1} are attributed to a stretching of the C-O bond [26], whereas the peak at 2885 cm^{-1} indicates a stretching of the C-H bond [27]. The spectrum highlights the complex molecular interactions and structural modifications occurring within the PEG-PMMA system, providing valuable information on the composition and behaviour of the material. Furthermore, the presence of O-H stretching [28] may be observed at a wavelength of 3426 cm^{-1} . Also presence of C-H bending is confirmed by detection of peaks at 1453 cm^{-1} , 1280 cm^{-1} , and 1297 cm^{-1} [27]. Essentially, the study shows that adding MWCNT nanoparticles to the basic PCM (PEG-PMMA) does not result in any extra peaks, as indicated by the absence of detectable peaks [29]. The results clearly demonstrate that there are no impurities or chemical reactions present in the development of (Ne-OPCM) composites. Furthermore, the findings ensure that there are no unwanted chemicals or chemical reactions during the creation of (Ne-OPCM) composites. The importance of maintaining the purity and integrity of synthesized materials cannot be overemphasized, highlighting their essential role in possible applications. The verified synthesis process verifies the original quality of the (Ne-OPCM) composites, hence enhancing their applicability for diverse applications. This highlights the need to preserve the

purity and integrity of the synthesized materials, which is a crucial element that enhances the potential uses of the (Ne-OPCM) composites. The established synthesis technique confirms the pure character of the materials and enhances their suitability for potential applications. The focus on purity and integrity is of utmost importance, establishing a strong basis for the expanded potential of the (Ne-OPCM) composites in many applications.

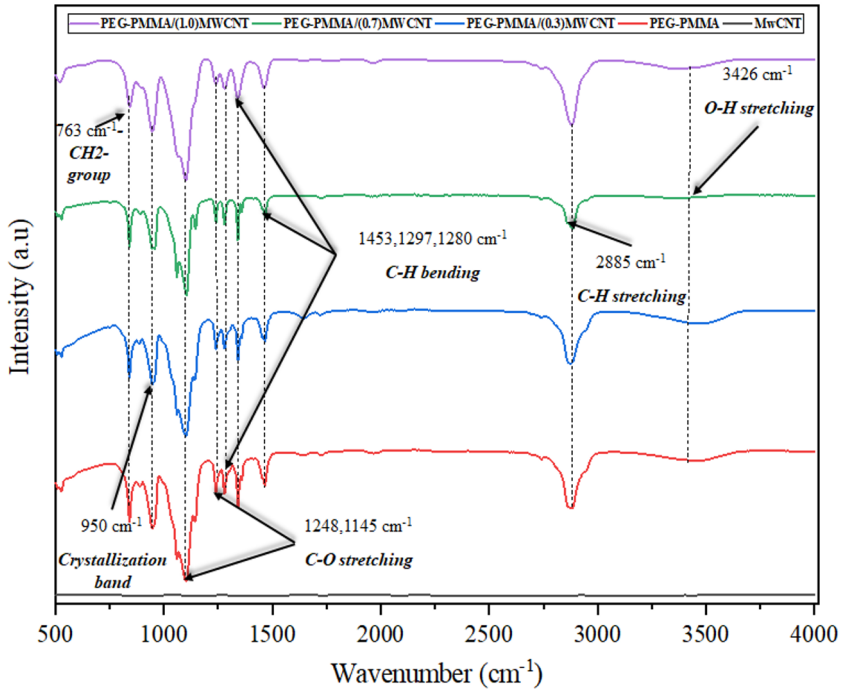


Fig. 3. Schematic diagram of FTIR curve of MWCNT nanoparticle, base PCM, and PCM composites.

3.3 Light transmissibility and absorptivity (UV-Vis) of (Ne-OPCM) composites

The light transmission and absorbance of base PCM and PCM composites were evaluated using a UV-Vis spectrometer, while weight percentages of MWCNT nanoparticles were varied. The range of MWCNT that absorbs ultraviolet radiation is 280–380 nm, visible electromagnetic radiation is 380–740 nm, and infrared radiation is 740–1400 nm at room temperature. An investigation finds MWCNT nanoparticle's effect on comparable properties in three weight fractions with base (PEG-PMMA) PCM. Fig. 4 and Fig. 5 visually depict the absorption and transmission properties of light at different concentrations in a wavelength range of 200 nm to 1400 nm. An experiment aims to analyze the relationship between the weight fraction of MWCNT nanoparticles in base PCM, composed of PEG-PPMA, and light absorption. Ne-OPCMs are used as volumetric absorbers in solar thermal energy storage applications. Significantly, over an entire period of investigation, these Ne-OPCM composites constantly remained in a liquid condition. This result highlights the potential of these materials as efficient means for absorbing and storing solar thermal energy. The work provides vital insights into the complex correlation between the concentration of MWCNTs in the PCM and their related light absorption capabilities. This enhances our comprehension of the suitability of materials in sustainable energy storage systems. The liquid PCMs' absorption capacity is frequently employed to ascertain the equilibrium temperature of the liquid. This work evaluated the optical properties of composites made of Ne-OPCM across a

range of wavelengths spanning from 200 to 1400 nm. Solar spectrum was compared to composite samples of (Ne-OPCM) utilizing interplanetary spectrum data obtained from Gueymard [30]. PCM composites, especially those containing MWCNT, are important in solar thermal energy storage. In this study, the solar spectrum transmissibility percentages for PCM composites with 0.3, 0.7, and 1.0 wt% MWCNT and PEG-PMMA base composition were carefully examined. The PCM composite containing 0.3 wt% MWCNT has extremely low transmissibility, 34.175 %, compared to 12.776 % for the standard PEG-PMMA PCM. This dramatic drop in transmissibility shows how MWCNT integration changes the composite's optical characteristics, suggesting a way to improve solar absorption. The discovered Ne-OPCM composites have increased absorption and low transmission. This makes Ne-OPCM composites ideal for solar thermal energy storage, a promising way to harness and use solar energy. The study shows that MWCNT-infused PCM composites might revolutionize solar-based technology and enable sustainable and efficient energy storage systems. Herein, present work concludes that incorporating MWCNT nanoparticles into PEG-PMMA composite PCMs has a substantial influence on solar thermal energy storage. The optical examination conducted in the wavelength range of 200 to 1400 nm reveals a significant decrease in transmissibility, especially in the Ne-OPCM composites. The composites, namely PCM composite at 0.3 wt% of the MWCNT, have a high ability to absorb energy and a low ability to transmit it. This makes them excellent options for storing solar thermal energy effectively. This work establishes a foundation for progress in using MWCNT-enhanced PCMs to maximize the absorption of solar energy. It also highlights a potential of these materials in creating thermal energy storage systems that are both sustainable and high-performing.

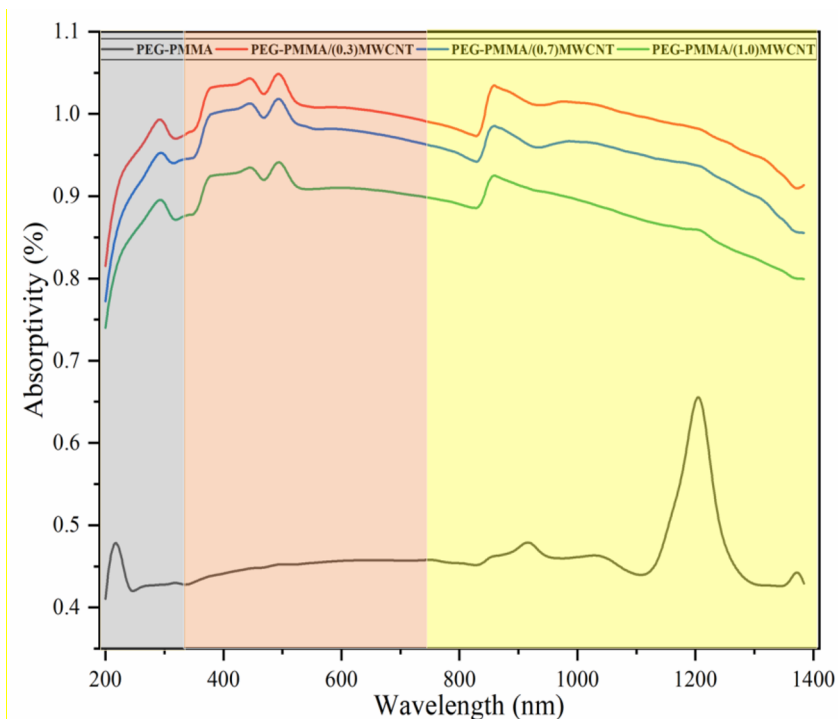


Fig 4. UV-Vis outcomes (Wavelength vs Absorptivity) for base PCM and (Ne-OPCM) composites.

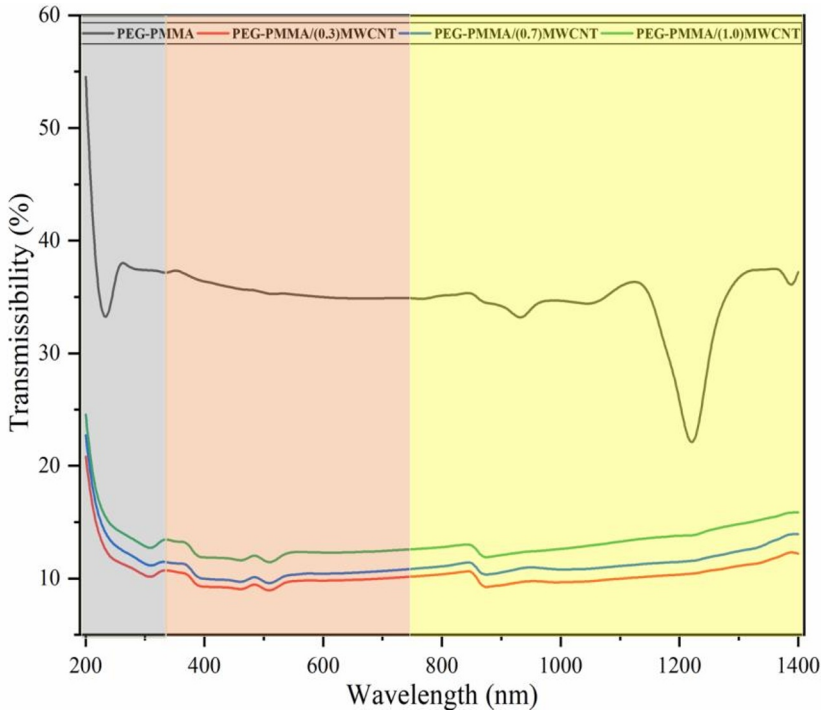


Fig 5. UV-Vis outcomes (Wavelength vs Transmissibility) for base PCM and (Ne-OPCM) composites.

3.4 Final decomposition temperature analysis (TGA) of (NePCM) composites

Thermal stability of PEG-PMMA/MWCNT composites was evaluated via thermogravimetric analyses (TGA). The mixed (Ne-OPCM) only break down into PEG-PMMA and MWCNT in this temperature range. The TGA analysis results for the (Ne-OPCM) are displayed in Fig. 6. Fig. 6 depicts the TGA graphs of all (Ne-OPCM), which show two degradation curves due to heat decomposition. The initial degradation curves describe the decomposition of PEG-PMMA in Fig 6. The temperature range of 235 °C to 430 °C is considered a key zone for the base (PEG-PMMA) PCM, as it undergoes significant deterioration, with up to 95 % reduction in its quality. Currently, the PEG-PMMA tends to disappear and experience deterioration. Significantly, the first instances of deterioration for PEG-PMMA occur at a temperature of 400 °C. In addition, PCM composites at 0.3 wt%, 0.7 wt% and 1.0 wt% of the MWCNT show deterioration maxima at temperatures of 415 °C, 425 °C, and 405 °C, respectively. These degradation temperatures indicate that PEG-PMMA/MWCNT composites have improved thermal stability compared with PEG-PMMA. The creation of a NePCM composite, caused by the clustering of MWCNT nanoparticles, may help in anticipating temperature degradation. The incorporation of MWCNT nanoparticles into (PEG-PMMA) PCM forms a solid dispersion, which effectively improves the thermal stability of the PEG-PMMA/MWCNT samples, as seen by the TGA curves. This indicates that the inclusion of MWCNT nanoparticles is essential for enhancing the thermal stability of a composite material. Additionally, dispersion of MWCNT to PEG-PMMA composites greatly improves their resistance to heat, as demonstrated by TGA. The incorporation of MWCNT leads to the formation of a solid dispersion, which enhances overall thermal stability in comparison to pure PEG-PMMA. The composites' degradation temperatures indicate excellent performance, with PCM composites at 0.3 wt%, 0.7 wt% and 1.0 wt% of the MWCNT showing greater maximum deterioration than pure PEG-PMMA.

The agglomeration of MWCNT nanoparticles in the composite leads to the creation of NePCM, which hinders premature degradation and presents a favourable option for applications that need exceptional thermal stability.

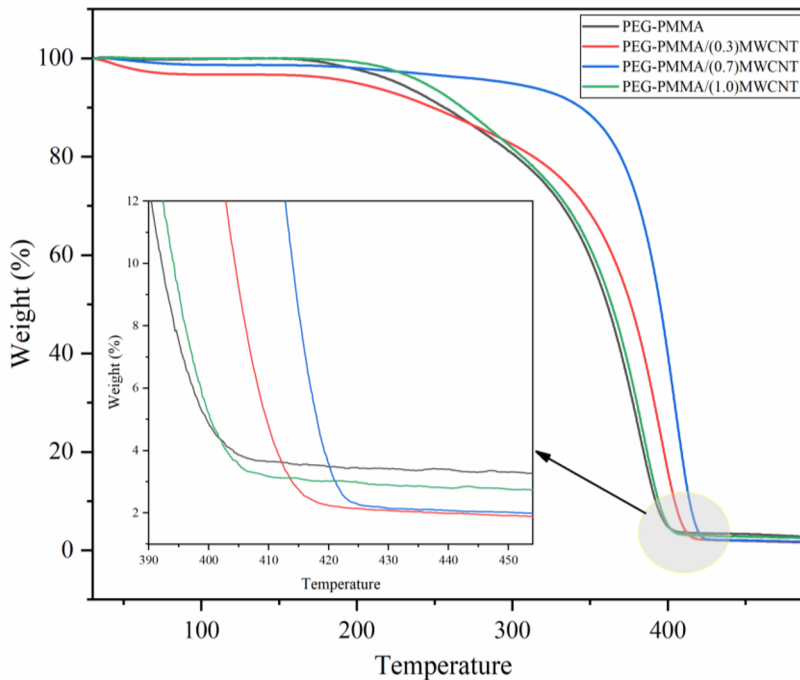


Fig. 6. TGA curve of base PCM and various weight percentage MWCNT nanoparticles enhanced (Ne-OPCM) composites.

3.5 Latent heat and the melting point of a newly synthesized PEG-PMMA/MWCNT (Ne-OPCM) composites

The latent heat of phase change materials (PCMs) is essential in preserving energy density and conforming to thermal energy storage (TES) limitations throughout the phase transition. Effective energy storage with PCMs depends on the incorporation of phase change enthalpy. Hence, the enthalpy related to a phase transition greatly enhances energy storage, and the efficiency of using enthalpy to release energy stored during charging process is crucial [31]. The present experimental study aimed to evaluate the latent heat and melting point of a PCM known as PEG-PMMA, as well as its newly synthesized composite. Fig. 7 displays the endothermic peaks of base PCM and PCM composites at 0.3 wt%, 0.7 wt% and 1.0 wt% of MWCNT in the prescribed sequence. The DSC curve of base PCM reveals a latent heat capacity of 129.39 J/g and a melting temperature of 39.3 °C. While some PCM composites established slight deviations in their thermograms, most demonstrated consistent endothermic peaks similar to those observed in pure PEG (Fig. 7). Upon analyzing the inflection points of the curves, it is evident that the melting temperatures for PCM composites at 0.3 wt%, 0.7 wt% and 1.0 wt% of the MWCNT are 37.5 °C, 40.4 °C, and 33 °C, respectively. A latent heat values of the newly created NePCM were determined to be 129.30 J/g, 139.66 J/g and 137.34 J/g for PCM composites at 0.3 wt% & 0.7 wt% 1.0 wt% of the MWCNT. The results demonstrate that the latent heat capacity of the novel NePCM increased by roughly -0.069 %, 7.93 %, and 6.144 % for MWCNT loadings of 0.3, 0.7, and 1.0 wt% to PEG-PMMA, respectively. To summarise, the work highlights the increase in the ability of

NePCM composites to store heat, emphasizing the potential for better heat transfer in applications that use PEG-PMMA and MWCNTs. The increase in absorption capacity of PEG-PMMA is ascribed to the involvement of MWCNTs. In addition, composites obtained demonstrate reduced melting temperatures as compared to pure PEG-1000. The results also demonstrate that NePCM composite, which is characterized by innovation, possesses a greater latent heat in comparison to a PEG-PMMA base material. The increase in latent heat can be attributed to formation of intermolecular interactions between the nanoparticle and a PCM. Significantly, the substitution of a significant proportion of the PCM with nanoparticles results in a net augmentation of the latent heat. The interaction between molecules and the replacement of mass are both important factors; when the interaction between molecules is stronger than replacement of mass, latent heat of a composite increases. On the other hand, if a replacement of mass is more significant, the latent heat falls. Moreover, the level of PCM mass substitution plays a crucial influence in determining latent heat capacity. Lower concentrations lead to a higher prominence of intermolecular interaction, which in turn causes an increase in latent heat capacity. Furthermore, a sufficient amount of PCM mass replacement increases, and there is a reduction in latent heat. A complex connection between intermolecular interaction and mass replacement plays a crucial role in determining latent heat of a composite [32].

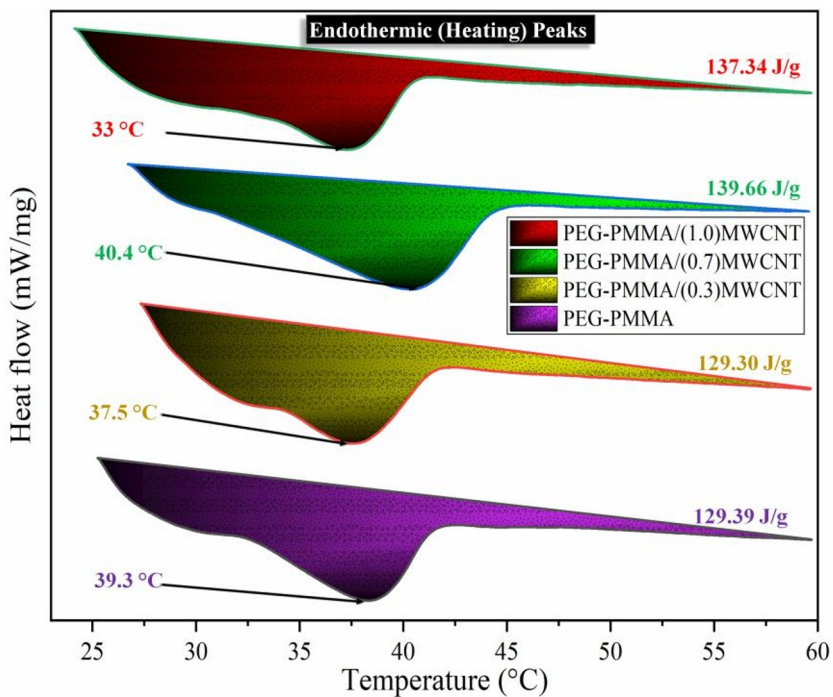


Fig. 7. Schematic diagram of latent heat and the melting point of a newly synthesized PEG-PMMA/MWCNT (Ne-OPCM) composite.

3.6 Thermal conductivity and thermal diffusivity of (Ne-OPCM) composites

Thermal conductivity of NePCM composites was evaluated at room temperature utilizing Tempus, a dual-needle SH-3 thermal analyzer. In this investigation, each sample's average of 10 readings was taken to determine thermal conductivity value. Results show that the thermal conductivity of (Ne-OPCM) composites varies from 0.267 to 0.501 W/mK under

static atmospheric conditions at room temperature, as represented in Fig. 8. Thermal conductivity augmentation [33] and thermal conductivity ratio [34] are two distinct parameters estimated by researchers. Results indicate a drastic improvement in thermal conductivity of a (Ne-OPCM) composite is 87.64 % with a thermal conductivity value of 0.501 W/mK at 0.7 weight fraction of MWCNT. And composite's thermal conductivity was 0.406 W/mK and 0.467 W/mK, increased by 52.05 % and 74.90 %, respectively, compared with the base PEG-PMMA (0.267 W/mK). According to Fig. 8, they strengthened the MWCNT nanoparticle concentration and enhanced the thermal conductivity of a (Ne-OPCM) composite. MWCNT nanoparticles are highly thermal conductive compared to the pure base (PEG-PMMA). The succeeding route will deliver a probable reasons for the increase in thermal conductivity of (Ne-OPCM) composites with different concentrations of MWCNT. Also, by adding the MWCNT with the base PCM, thermal transportation can occur; due to this, the phonon transfer mechanism rate is improved, and overall thermal conductivity of a composites is also improved. At low concentration of MWCNT, a coupling of nanoparticles with base PCM might not occur, which is a main reason for the degradation of mean free path of a phonon with phonon-boundary scattering [35]. While increasing the MWCNT concentration, the uniform thermally conductive path or network occurs with the base PCM; due to this, a strong coupling is formed between the PCM and nanoparticle to increase thermal conductivity of (Ne-OPCM) composites. Finally, the agglomeration of nanoparticles leads to decreased thermal conductivity of (Ne-OPCM) composite at 1 wt% of MWCNT. A coupling between nanoparticles and base PCM is affected by agglomeration, which is more when the concentration of MWCNT was increased from 0.7wt% to 1wt%.

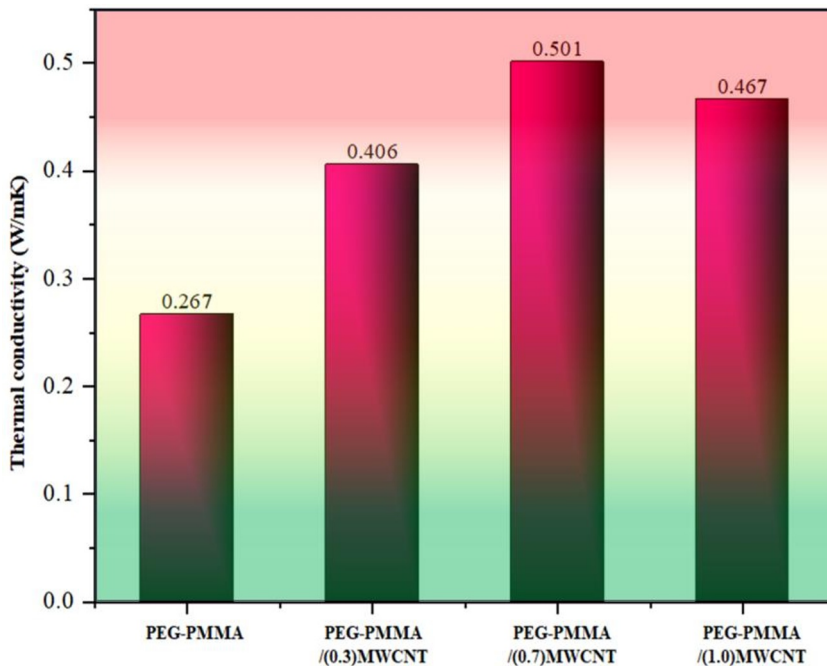


Fig. 8. Thermal conductivity results of base PCM and (Ne-OPCM) composites.

4 Conclusion

In summary of the present work, the ultra-sonication method successfully prepared PEG-PMMA/MWCNT to (Ne-OPCM) composites. The findings show that base PCM and MWCNT nanoparticles were uniformly spread and incorporated into a porous network structure of PMMA. Due to this, the chemical stability of the PEG-1000 is enhanced, and the steric hindrance effect is reduced. Also, MWCNT was physically linked with a PEG-PMMA matrix and did not contribute to polymerization. The thermal conductivity of stable (Ne-OPCM) composites is noticeably enlarged with an increment of MWCNT loading contents. The NePCM composites showed the best thermal conductivity at a concentration of 0.7 wt% MWCNT nanoparticles. This resulted in a significant improvement of 87.64 %, increasing thermal conductivity from 0.267 W/mK to 0.501 W/mK compared to a pure PCM. The incorporation of MWCNT not only enhanced the heat conduction ability of the NePCM composites but also increased their heat absorption capacity and thermal stability. Nevertheless, when the weight percentage of MWCNT increased from 0 to 1.0 wt.%, thermal conductivity of NePCM composites decreased compared to a composite with a 0.7% weight fraction of MWCNT nanoparticles. An ideal concentration of 0.7 wt% is indicated for getting the highest thermal conductivity in the Ne-OPCM composites. The decrease in size was mostly ascribed to the clustering of nanoparticles within the PCM. Moreover, increase in heat conductivity of a composite material was attributed to an excellent dispersion and substantial aspect ratio of MWCNT, which formed a thermally conductive network inside the PEG-PMMA matrix. Significantly, all the composites produced (Ne-OPCM) showed advantageous heat storage density and stability. The exceptional thermal properties of the PEG-PMMA/MWCNT composites make them highly favourable for use in a range of applications, such as EMI shielding, anti-electrostatic materials, and bipolar plates in proton exchange membrane fuel cells. These materials are particularly valuable in situations where effective temperature control is of utmost importance.

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