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ENABLING THE THERMAL PERFORMANCE OF LAURIC ACID PHASE CHANGE MATERIAL INTEGRATED WITH MULTIWALL CARBON NANOTUBES FOR SUSTAINABLE THERMAL ENERGY STORAGE SOLUTION

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Abstract

Fatty Acid Phase Change Materials (PCMs) have great potential in this aspect. Nevertheless, their intrinsically limited heat conductivity greatly hinders their practicality. This study presents an experimental examination into the preparation and characterization of nanocomposites consisting of lauric acid PCM and Multiwall Carbon Nanotubes (MWCNT) nanoparticles (NPs). The two step preparation scheme was adopted to prepare nanocomposite. The prepared samples were evaluated for thermal conductivity, chemical stability, latent heat enthalpy, photo-transmissibility, and thermal stability characteristics. It was evaluated the lauric acid's thermal conductivity enhanced from 0.19 W/m·K to 0.273 W/m·K by adding 0.4 wt% of MWCNT NPs. Besides, upon evaluation utilizing FTIR, it was found that all the produced samples were chemically stable. Furthermore, base PCM's differential scanning calorimeter (DSC) revealed 175 J/g of melting latent heat enthalpy and nanocomposites exhibited 161, 160 and 176 J/g of latent heat enthalpy for 0.2, 0.4 and 0.6 wt% addition of MWCNT NPs with slight variation in melting temperature. All the composites were found to be thermally stable up to 140°C by the Thermogravimetric Analyzer (TGA), and the addition of NPs had no effect on the chemical structure of base PCM. Hence, lauric acid PCM with enhanced thermal conductivity and photo-absorption can be opted for energy storage in medium range temperature applications.

Keywords: Lauric acid, Nanoparticles, Phase change material, Thermal energy storage, Thermo-physical properties.

1. Introduction

Energy may be stored by several processes, such as electrical, mechanical, thermal, magnetic, and electrochemical techniques [1]. The optimal use of any kind of energy relies on its effective storage system. Thermal energy storage systems (TES) are attractive approach to storing thermal energy, since it allows for the direct use of this energy without the need for conversion into another form. Therefore, efforts should be made to enhance and streamline the efficiency of energy storage devices while ensuring that they provide high energy storage capacity at a consistent operating temperature. The growing interest in sustainable energy development is being shown in thermal energy storage techniques based on phase change material (PCM). PCM has the capacity to change its solid state into liquid state while keeping a consistent phase change temperature, making it an excellent choice for storing thermal energy [2].

PCMs are a kind of material with latent heat storage that fall into three categories: eutectic, inorganic, and organic [3]. These substances experience energy absorption or release via the mechanisms of melting or solidification when the surrounding temperature reaches the melting temperature of PCMs. As a result, PCMs can store energy. However, PCMs exhibit inadequate thermal conductivity, resulting in a diminished ability to retain heat [4]. Due to their superior thermo-physical characteristics and quicker charging and discharging rates compared to regular phase change materials, nanoparticle integrated phase change materials are more appealing for ambient thermal energy storage systems.

In order to solve the low thermal conductivity problem, the researchers amalgamated PCMs with various external fillers, including metal foam, carbon compounds, and nanoparticles [5]. Among them numerous research work has been completed by adding titanium dioxide, graphene, copper [6], MXenes [7], bio based [8] and other nanoparticles in PCM, like Owolabi et al. [9]. The use of metal and carbon nanoparticles into these investigations is intended to enhance the thermo-physical characteristics of both organic and inorganic PCMs. Reliability of nanoadditives on the thermal enhancement of nanofluids and nanocomposites has been widely discussed and in the special issue of edited by Al-Kayiem [10]

For instance, Kumar et al. [11] investigated organic paraffin PCM for thermal conductivity improvement by integrating silicon nitrides nanoparticles. The findings demonstrated that the nanoparticles are uniformly diffusing inside the paraffin matrix and that the base paraffin's thermal conductivity was significantly enhanced by the nano silicon nitrides particles. The addition of 2 wt% of nanoparticles enhanced heat transfer rate to 33.4% with thermal and chemical stability. Ghafari et al. [12] conducted research on the melting behaviour of zinc oxide nanoparticle-reinforced PCM. The results of the experiments showed that the addition of 0.1% and 0.2% by the mass fraction zinc oxide nanoparticles, respectively, would provide improvements in thermal conductivity of 28% and 27%. Al-Kayiem and Lim [13] reported the performance enhancement of a solar water heater integrated with a nanocomposite PCM TES. Paraffin wax as a PCM and a nanocomposite of paraffin wax with 1.0 wt% of 20-nm nano-Cu particles were tested as the energy storage medium for in compacted solar water heater. They concluded that measurement result of the tank water temperature at 7:00 AM, after 24 h of operation, was 35.1ºC when the system operated without TES, while the operation with the PCM and with the Cu-PCM nanocomposite resulted in 40.1 ^{o}C and 40.7 ^{o}C tank water temperatures, respectively.

In a different study by Pugalenthi et al. [14] , a unique nanocomposite PCM was produced by forming the eutectic PCM combination with organic fatty acids like stearic acid (SA) and lauric acid (LA). In addition, by suspending nano silicon-carbide NPs to create a composite PCM. The thermal conductivity was enhanced up to 75% by adding 0.075 volume% of silicon carbide NPs and thermal stability of eutectic LA-SA PCM were enhanced. Further, theoretical and experimental investigation was conducted on nanocomposites based on paraffin wax, including varying weight percentages of 0.5, 1.0, and 1.5 weight% (wt%) of NPs of iron, copper, zinc, and aluminium. It is found that the addition of copper and zinc nanoparticles to the nanocomposite at a concentration of 1.5 wt% increased its thermal conductivity by 20.6% and 61.5%, respectively. In the nano-enhanced PCM composites, better thermal energy storage can be seen, particularly in solar and thermal energy storage integrated systems [15]. Furthermore, in other study, lauric acid PCM was integrated with hexagonal boron nitride nanoparticles by adopting two step method. As per results, the thermal conductivity enhancement of 36.3% was achieved by adding 3 wt% of nanoparticles [16]. Moreover, Samiyammal et al. [17] prepared nanocomposites of paraffin and magnesium oxide nanoparticles. The mass fractions of 0.25, 0.5, 0.75 and 1 wt% were adopted for nanocomposite thermal conductivity evaluation. The maximum enhancement in thermal conductivity was observed as 55.5% at 1.0 wt% addition of nanoparticles.

It is evident from literature that the thermal performance of the base PCM were improved by including nanoparticles. Besides, PCM can be used in different applications like solar heating [18] and battery thermal management. This concept has sparked a substantial revolution in several fields of application, especially in thermal storage. Herein, organic lauric acid PCM has been selected due to its higher latent heat enthalpy. Further, to evaluate its thermal performance the addition of highly conductive 1D multiwall carbon nanotube (MWCNT) particles has been opted. The base PCM and its nanocomposites added with MWCNT at mass fractions of 0.2, 0.4, and 0.6 wt% were characterized for thermo-physical evaluation. Generally, PCMs like lauric acid exhibit low thermal conductivity and low photo-absorbance, which restrict their implementation in applications. As per our previous study [19], 0.4 wt% added MWCNT lauric acid exhibited higher thermal conductivity. Therefore, the objective of this work is to further evaluate the photo-absorbance, chemical stability, latent heat enthalpy and thermal stability of MWCNT added lauric acid PCM.

2. Materials and Methods

This section provides a full discussion of the materials, composite production processes, and characterisation techniques used in this experimental investigation.

2.1. Materials

Lauric acid ($C_{12}H_{24}O_2$), an organic phase change material, was acquired via R&M, a supplier corresponding to Biotek Abadi Sdn. Bhd., which is headquartered in Malaysia. Further, nanoparticles of MWCNT were integrated into the PCM to increase the thermo-physical properties of the material. The Company Cheap tubes in the United States supplied the MWCNT with an average diameter of 20 nanometres.

2.2. Preparation method for nanocomposites

A two-step method that was based on lauric acid PCM and MWCNT nanoparticles was utilized to produce the nanocomposite PCM. In the initial step, a specific quantity of LA was measured and put into a glass bottle using an electronic balance (MODEL: EX 224 OHAUS) in accordance with the selected proportion. The glass bottle was subsequently set on the heating plate (RCT, BASIC IKA), and the temperature was heated to 60 ℃ until the material was entirely melted. In second step, nanoparticles with predefined ratio were weighted at weight balance and inserted into melted base PCM. Afterwards the sample were placed at ultra-sonicator (model: FS 1200N) for 30 minutes for homogeneous mixing. Figure 1 illustrates the preparation scheme for lauric acid and MWCNT based nanocomposite. Further, nanocomposites were prepared by adding 0.2, 0.4, 0.6 wt% of MWCNT in lauric acid. Therefore, the nanocomposites are labelled as LA, LM-0.2, LM-0.4, and LM-0.6 for base PCM, 0.2, 0.4, and 0.6 wt% of MWCNT added nanocomposites, respectively, as shown in Table 1 and will be followed throughout the manuscript.

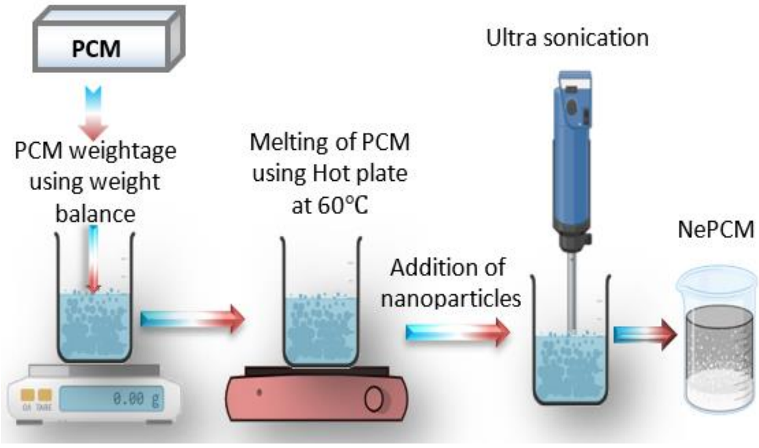

Fig. 1. Preparation scheme for nanocomposites.

Table 1. Prepared composites codes.

Code	Lauric acid (wt%)	MWCNT (wt%)
LA	100	0
LM-0.2	99.8	0.2
LM-0.4	99.6	0.4
LM-0.6	99.4	0.6

2.3. Characterization instruments

After preparation, the prepared composites were characterized by adopting various characterization techniques. The chemical stability was checked by utilizing Fourier transform infrared spectroscopy (FTIR) instrument by Perkin Elmer. Besides, photo-absorption of composites were evaluated by Ultraviolet visible spectroscopy (UV-Vis) by Perkin Elmer USA. Further, thermal conductivity of composites was assessed by adopting Tempos equipment by meter group. Furthermore, the latent heat enthalpy was measured by Sirius 3500 NETZSCH Differential Scanning Calorimeter. Moreover, the thermal stability of composites was evaluated by Thermo-gravimetric analyser by Perkin Elmer instrument model TGA 4000.

3. Results and Discussion

The following section provides the experimental characterization findings of the sample containing multi-walled carbon nanotubes (MWCNT) distributed in PCM. The findings include FTIR spectra curves to verify the chemical stability, thermal conductivity evaluation, UV-Vis curves to assess the optical absorption and transmission, and DSC heat flow rates to demonstrate the changes in energy storage capacity of the prepared composite PCM.

3.1. Chemical stability evaluation for composites

Fourier transform infrared spectroscopy (FTIR) is a valuable analytical technique employed for investigating the molecular composition of samples by quantifying the absorption and transmission of infrared light. This methodology is predicated on the principle that distinct chemical bonds exhibit selective absorption of infrared radiation at characteristic frequencies, thereby facilitating the detection and quantification of a diverse range of compounds within a given sample. The transmission spectra for materials such as LA, MWCNT, and the LM composite, featuring varying weight percentages of MWCNT, are depicted in Fig. 2.

By comparing the results obtained from pure LA with those obtained from composite materials, it becomes possible to discern the influence of additional components such as MWCNT on the chemical composition of LA. The FTIR curves elucidate that the peaks corresponding to pure LA and the LM composite materials remain consistent, signifying the preservation of LA's functional groups.

Detailed analysis of the intensity, wavelength, and vibrational modes associated with different functional groups yields valuable insights into the chemical characteristics of these compounds. The main peaks for base PCM and all nanocomposites were found at 2912, 2850, 1691, and at 933 cm^{-1}. Notably, the strong stretching vibrations observed at 2912, 2850 cm^{-1} in alkane groups (-CH3 and -CH2) provide evidence for the presence of saturated hydrocarbon chains within the molecules. Furthermore, peak 1691 cm^{-1} [16] indicates the variable intensity of the carbonyl group (C=O) double bond in alkenes suggests differing levels of symmetry within the molecular structures under investigation.

Besides, peak at 933 cm-1 relates to –OH out of plane bending vibration of functional group. Such observations underscore the utility of FTIR spectroscopy in elucidating the intricate molecular composition and chemical properties of materials, thereby advancing our understanding for prepared composites. The FTIR evaluation demonstrated that all composites showed same peaks and functional group that confirmed chemical stability of all prepared nanocomposites and showed resemblance to recent literature reported [20].

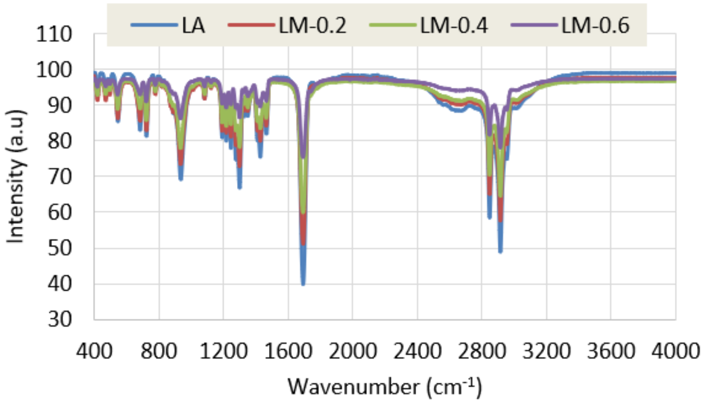

Fig. 2. FTIR evaluation of base PCM and MWCNT added nanocomposites.

3.2. Photo-absorbance evaluation for prepared composites

A higher level of photonic absorptivity and an inferior transmission level are essential for PCMs. This is because the primary energy source for thermal energy retention in PCMs for photo-to-thermal energy conversion is the sun's radiation. Nonetheless, most organic PCMs are transparent and have noteworthy light transmission characteristics. Therefore, the Ultra-Violet Visible Spectrum instrumentation has been used in this research work to assess the light transmittance characteristics of base LA and its nanocomposites. Hence, this study focusses on examining the light absorption and transmission properties of LA and its nanocomposites throughout a wavelength range of 250-1400 nm.

The photo-transmittance curve for the produced composites is shown in Fig. 3. The measured light transmittance of LA turned out to be 76%. Similarly, the measurement of photo-transmittance for LM-0.2, LM-0.4, and LM-0.6 appeared to be 18.8, 15.3, and 14.2%, respectively. The maximum reduction in transmissibility as compared to base was found to be 81.32% for LM-0.6 nanocomposite. However, the nanocomposite LM-0.4 reduced 79.8% photo-transmittance as compared to base LA. Since the transmittance and adsorption are inversely proportional in relation. The nanocomposite shows lower photo-transmittance that leads to better photo-absorption. The higher absorption rates for nanocomposites attributed to excellent photo-absorptivity of MWCNT nanoparticles and black colour of composites [21].

3.3. Thermal conductivity analysis of composites

The thermal conductivity of the composite LM, comprising LA as the base PCM and MWCNT as the nano-additive, was investigated across varying weight percentages of MWCNT (0.2, 0.4, and 0.6) by using Tempos instrument of meter group at room temperature.

As per our previous study [19], the thermal conductivities measured were 0.23, 0.273, and 0.235 W/(m·K), respectively, as shown in Fig. 4. Whereas the thermal conductivity of base PCM LA was 0.19 W/(m·K). The samples were denoted as LM-0.2, LM-0.4, and LM-0.6. Notably, a decrement in thermal conductivity was observed at 0.6 wt.% of MWCNT compared to the LM-0.4 sample. This decline can be attributed to several factors. Firstly, at higher concentrations of MWCNT, the agglomeration of nanoparticles becomes more pronounced, leading to increased thermal resistance within the composite [18]. Additionally, excessive loading of MWCNT can disrupt the structural integrity of the composite, impeding the efficient transfer of thermal energy. Moreover, beyond a certain threshold, further incorporation of MWCNT may contribute negligibly to thermal conductivity enhancement, thus exhibiting diminishing returns. The percentage increment in thermal conductivity for the LM-0.4 sample compared to pure PCM LA was noted at 43.68%, indicating a moderate enhancement in thermal transport properties achieved through the optimized concentration of MWCNT within the composite matrix.

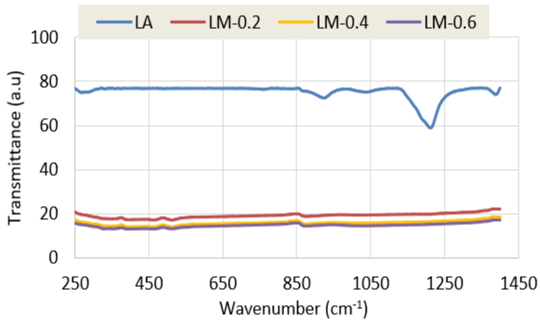

Fig. 3. Photo-transmittance evaluation of PCM and nanocomposites.

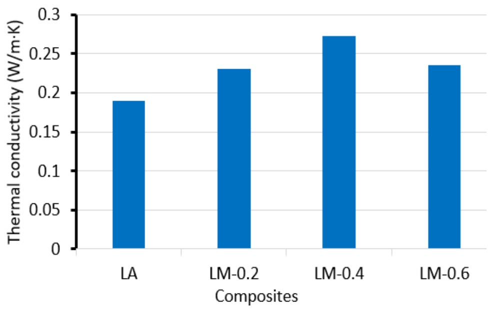

Fig. 4. Thermal conductivity analysis for LA and MWCNT nanocomposite.

3.4. Latent heat enthalpy evaluation for composites

The latent heat enthalpy of base and prepared nanocomposites was analysed using Sirius 3500 NETZSCH Differential Scanning Calorimeter. As can be observed in Fig. 5, the phase shifts that occurred in the base lauric acid PCM and subsequent nanocomposite occurred during both an endothermic and an exothermic process. To calculate the latent heat for the PCM containing lauric acid and its nanocomposites, it is necessary to conduct an analysis of the integral of the region that contains the phase transition curves. Therefore, as per the measurement, the base lauric acid exhibited 175 J/g of latent heat melting enthalpy with onset melting temperature of 46 ℃. However, the nanocomposite LM-0.2, LM-0.4, and LM-0.6 exhibited 161, 160 and 176 J/g of latent heat of melting enthalpy with slight variation in onset melting temperature, as shown in Fig. 5. The decrement in latent heat may be explained by the addition nanoparticles, which causes nanoparticle to partially replace PCM. This phenomenon happens when a significant mass fraction of NPs is introduced, which prevents the re-alignment of PCM molecules because a portion of PCM is substituted by NPs. The results that were obtained for the enthalpy of phase change are within acceptable range and can be considered for energy storage application purpose.

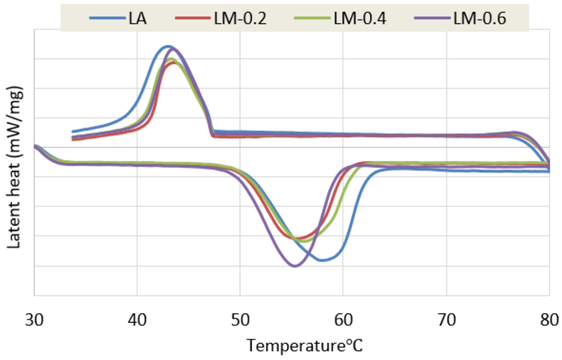

Fig. 5. Latent heat evaluation for endothermic and exothermic curves.

3.5. Thermal degradation evaluation of composites

Thermogravimetric analysis (TGA) is used to investigate the thermal deterioration of a sample that has been prepared and exposed to numerous cycles of heating and cooling. A TGA is used to quantify weight loss % over temperature to test thermal stability. The measurement is conducted in a nitrogen environment, with a standard heating rate of 10 °C per min. The temperature range for the measurement is from 30 °C to 280 °C. The Thermogravimetric examination results indicated that both the base PCM and nanocomposite exhibited a comparable pattern in terms of the thermal degradation of the entire samples, as seen in Fig. 6. The addition 0.2 and 0.4 wt.% of MWCNT nanoparticles significantly increases the thermal degradation temperature of nanocomposites, causing a dramatic rise from the beginning point to the end points of the curve. This increment is due to formation of thermal barriers networks formed between PCM and MWCNT nanoparticles due to van der Waal interaction and capillary forces [22]. However, slight decrement in weight degradation is shown by 0.6 wt.% of MWCNT added to PCM. All, the samples follow same degradation pattern within 10℃ range of temperature. All samples show zero weight% degradation till 140℃ and 100% weight degradation between 240 °C to 250 °C.

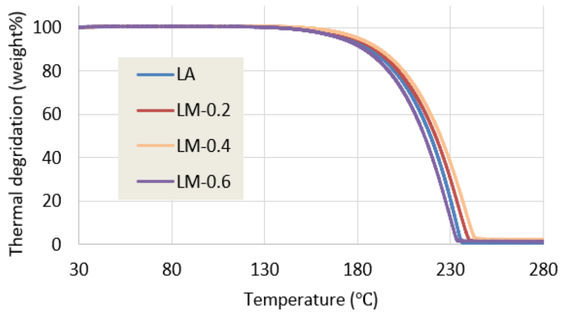

Fig. 6. Thermal degradation stability evaluation of prepared nanocomposites.

4. Conclusions

The purpose of this study is to prepare nanocomposites PCM by integrating high thermal conductivity nanoparticle, such as nano-MWCNT into lauric acid PCM at weight percentages of 0.2, 0.4, and 0.6. The following findings and inferences were established:

- The base lauric acid exhibited thermal conductivity of 0.19 W/m·K. However, thermal conductivity of nanocomposites added with 0.2, 0.4, and 0.6 MWCNT nanoparticles showed 0.23, 0.273, and 0.235 W/m·K, respectively. The highest thermal conductivity enhancement occurred to be 43.68% at 0.4 weight% of MWCNT nanoparticles.
- The base lauric acid displayed 175 J/g latent heat enthalpy of melting. On the other hand, nanocomposite integrated with 0.2, 0.4, and 0.6 weight% of MWCNT exhibited 161, 160, and 176 J/g of latent heat of melting.
- The weight degradation measurement showed no weight loss till 140 ℃ for base and nanocomposites. Further, the addition of 0.2 and 0.4 MWCNT nanoparticles has enhanced the weight degradation temperature in comparison to base PCM. However, 0.6 MWCNT wt.% added nanocomposite exhibited slight decrease in weight degradation temperature as compared to base. All composite showed 100% weight degradation between 240 to 250 ℃.
- It could be concluded that the prepared nanocomposite would be beneficial for energy storage applications with melting temperatures in the medium range.

Nomenclatures

Wt%	Weight percentage

Abbreviations

DSC	Differential Scanning Calorimeter
FTIR	Fourier Transform Infrared Spectroscopy
LA	Lauric acid
MWCNT	Multiwall carbon nanotubes
PCM	Phase Change Materials
SA	Stearic acid
TES	Thermal Energy Storage
TGA	Thermal Energy Storage
UV-Vis	Thermogravimetric analysis

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