

Research Article

Synthesis of Modified Phase-Changing Material with Latent Heat and Thermal Conductivity to Store Solar Energy Using a Carbon Nanotube

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MicroPCMs' excellent thermal capacity and photothermal translation features benefit solar energy storage applications significantly. A successful in situ polymerization procedure was employed to build microencapsulated phase-change materials using n-hexadecanol as the core and melamine-formaldehyde resin as the outer shell, and the thermal characteristics of the microPCMs were evaluated. In terms of micromorphology, the incorporation of hydroxylated carbon nanotubes into microPCMs with a compact shell has little effect on their spherical structure. MicroPCMs' melting heat and latent heat are both 51.5°C with a 0.2 weight percent dose of hydroxylated carbon nanotubes, and n-energy hexadecanol's storage efficiency is determined to be 75.25 percent. Thermal conductivity and photothermal conversion efficiency of microencapsulated phase-change materials engendered with increased hydroxylated carbon nanotube dosage have improved significantly, laying the foundation for improved photothermal storage efficiency. When 0.6 weight % hydroxylated carbon nanotubes are added to the mixture, microencapsulated phase-change materials have a thermal conduction of 0.3597 Wm⁻¹.K⁻¹ and 181.5 J.g⁻¹. Additionally, all of the improved microPCMs show exceptional thermal stability across 500 heat cycles. Because of their large thermal capability and efficient photothermal conversion, the new microPCMs appear to be an appealing option for solar energy storage in direct-absorption solar collector systems.

1. Introduction

Many people believe solar energy to be among the best energy sources available, both theoretically and practically, because it is both clean and renewable [1]. The usage of solar thermal energy is an efficient approach to harness solar by

absorbing radiation, helping to relieve the energy crisis and environmental issues that result from our continued reliance on fossil fuels. Direct absorption of solar light and subsequent thermal energy generation are possible due to the device's internal working fluid composition [2–4]. The physical change of a phase-change material will transform from

the solid state to liquid, culminating in heat absorption, and heat is released whenever the temperature reaches the freezing point during the thermal cycling phase. Working fluid characteristics and photothermal conversion performance are unquestionably linked to DASC efficiency. Microencapsulated phase-change materials (microPCMs) become extensively employed in processing fluids in recent years due to the difficulties of storing considerable amounts of solar radiation energy utilizing the practical means of storing heat [5]. Latent heat storage is a technique used by these materials to retain energy. In order to construct core-shell microPCMs, the phase-change materials are encased in film and their feature sizes range from nanometres to micrometres [6–8]. Because they are employed as the core materials, microcapsule PCMs can collect, accumulate, and subsequently proclaim a significant quantity of thermal inactivity with very minor heat variations during the phase transition method. For example, microencapsulation of PCMs can help prevent leakage, control capacity change, and enhance temperature in a particular surface area during phase transitions [9, 10]. Phase change materials are used in a range of businesses, which include solar plants, photovoltaic energy processes, aviation industry, and preservation of food materials. There has also been a great deal of attention paid to microPCMs' realistic applications for building energy storing and the thermal control of microelectronic parts and heat-altered fabrics [11].

The most typical components of microPCMs with a stable core-shell structure are PCMs and inert organic or inorganic elements [12, 13]. There are a wide range of organic PCM materials that have excellent characteristics such as high chemical stabilization, less supercooling, moderate capacity fluctuations, moderate harmfulness and little abrasion, and low supercooling. With its high purification, low cost, high latent heat, and heat constraints of 22–60°C, n-dodecanol is a popular choice for making microPCMs [14–16]. n-Hexadecanol and n-octadecanol are also commonly employed. A microPCMs' shell is made up of a variety of materials, including organic and inorganic ones. PCMs can be encapsulated using a broad variety of materials, including MF resin, PMMA, UF, polystyrene, polyurethane (PU), silica, TiO₂, and CaCO₃.

To preserve the core components throughout the solid-liquid transition process, high molecular polymers offer several benefits over inorganic material, such as easy manufacturing, high compatibility, and superior compactness [17–19]. To create microPCMs with a high-heat storage capacity, researchers have looked into using crosslinked MF resin, which is easy to prepare and stable once it is encapsulated. MicroPCMs' heat absorption and release rates are adversely affected by the poor thermal conductivity of MF resin and other polymer shell materials. The practical implementation of polymer-based microPCMs in temperature management and solar energy storage remains a significant problem. Inorganic fillers with high thermal conductivity, like carbon or metallic oxide, have been included into the core and shell materials in several studies in an attempt to increase thermal conduction, thermal storing capability, and uniform photothermal adaptation. Phase-change micro-

capsules with capric acid as core and graphene oxide (GO) as shell were created by [20] using in situ polymerization. At ambient temperature, the thermal conduction of microencapsulated phase-change materials with a graphene oxide dosage of 0.9 wt percent was 75.1 percent higher. PCMs and specific heat of the graphene oxide-altered microencapsulated phase-change materials were almost equal in the next 100 thermal cycles, confirming the increased thermal stability of the modified microPCMs. Reference [21] examined the thermal characteristics of microPCMs, synthesizing n-dodecanol/MF resin microcapsules containing GO as part of the process. Addition of 0.6 percent to micro PCMs with the greatest oxidation degree occasioned in an enhanced in thermal conduction by 115%, which considerably improved thermal storage efficiency. Nano alumina was used by Jiang et al. to decorate microPCMs with a paraffin wax core and a poly (methyl methacrylate-co-methyl methacrylate) shell. Heat transmission in microPCMs can be considerably enhanced by the addition of nano-aluminium oxide. Once the nano-aluminium oxide dose was 16 weight percent of the monomer mass, the thermal conduction of the microencapsulated phase-change material was 93.41 J·g⁻¹. In situ polymerization was used by [22] to create paraffin wax/UF resin microcapsules containing a variety of nanoparticles, including Al₂O₃, CuO, and TiO₂. Using nanomaterials to strengthen polymer-based microPCMs has shown that they can increase their heat conductivity [23]. Carbon nanotubes, a type of 1-dimensional carbonaceous material, are popular reinforcement nanomaterials for composites since, high feature ratio, Excellent thermal conduction (up to 3000 W m⁻¹ and a higher thermal conduction of 0.586 W m⁻¹ K⁻¹), less density, and admirable photographic absorption. CNTs may also be used in conjunction with other materials to improve the thermophysical characteristics and photovoltaic translation behaviour of mixture [24]. As a result, they represent one of microPCMs' most promising thermal-conductive fillers. It is simple for CNTs to aggregate and have less dispersion in the synthetic microcapsule system because of their passive surface. The surface chemical composition of CNTs must be altered. Concomitant acid treatment by [25] increased the hydrophilic characteristics of CNTs, which were subsequently in situ polymerized in order to form CNTs/MF resin microcapsules with CNT reinforcement. To validate the melting heat content of the microencapsulated PCMs, they were subjected to 20 cycles of heating and cooling. The thermal conduction of microencapsulated phase-change materials was improved by 25th percent by the addition of 1.67 weight percent carbon nanotubes. They created an invention of double-walled n-octadecane microcapsule with an inner layer of melamine formaldehyde resin and an outside layer of carbon nanotube-poly Na(4-styrenesulfonic acid), utilizing the self-assembly procedure [26]. There was a considerable increase in the microPCMs' thermal response time, cooling efficiency, and thermal stability. MicroPCMs/epoxy resin composite has a thermal conductivity of 0.30 W m⁻¹·K⁻¹.

While [27] used O₂-plasma to produce CNTs, they used CNT-based microcapsules to analyze the electrical and mechanical characteristics of n-octadecane/melamine urea

formaldehyde resins. The thermal conduction and mechanical characteristics of microencapsulated phase-change materials with CNTs added to the polymer arrangement were significantly enhanced [28]. The thermal conduction of microencapsulated phase-change materials was increased by 225% when carbon nanotubes were added to the polymer arrangement. A graphene oxide-carbon nanotube hybrid filler enhanced the thermal characteristics of n-dodecanol/melamine formaldehyde resin microcapsules, which had a synergistic effect [29]. MicroPCMs' thermal conductivity improved by 195% when a hybrid filler was added at 0.6 wt percent, although the latent heat was reduced somewhat. We discovered that the microPCM-dispersed slurry has an excellent light absorption capacity for solar energy storage. Carbon nanotubes with stearyl alcohol (CNT-SA) grafted onto them were used in the experiment devised by [30].

Only $47.7 \text{ J} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$ of latent heat was released in the microPCMs, but their thermal conductivity was increased by 79.2 percent. The results of the trials clearly show that CNT nanofillers may be employed to greatly boost the thermal conductivity of microPCMs synthesized by various methods [31]. The latent heat of microPCMs, on the other hand, falls significantly with increasing CNT concentration. If the specific heat values of the CNT-changed microencapsulated phase-change materials are not optimized, the thermal storage capacity will be drastically reduced. Research on the photovoltaic translation efficiency of CNT-modified microPCM solar energy storage devices has also been under-researched [32]. Thermal conductivity and photovoltaic translation in microencapsulated phase-change materials have mostly been studied using hydroxylated carbon nanotubes (HO-CNTs). It's still being created MicroPCMs with increased heat storage capacity, like the Hydroxylated-Carbon Nano Tubes-enhanced MicroPCM [33]. In situ polymerization was employed in this investigation to generate n-hexadecanol- and MF resin-coated hydroxylated carbon nanotube-changed microcapsules. In microPCMs, n-hexadecanol was chosen as the primary material owing to its maximum heat storing capability and acceptable phase transition temperature (50°C) ($240 \text{ J} \cdot \text{g}^{-1}$).

2. Experimental Section

2.1. MicroPCMs Modified with HO-CNTs Synthesized. HO-CNT enhances carbon nanotube solubility and dispersibility while decreasing contact resistance. Its applications include energy storage, device modelling, thin-film electronics, and coatings. In situ polymerization was used to create the HO-carbon nanotube-enhanced n-hexadecanol/melamine formaldehyde resin microcapsule. The HO-CNT-modified microPCMs were synthesized in three conventional processes.

2.1.1. Shell Prepolymer Preparation. A tiny beaker was filled with 20 ml of deionized water, and a probe-type ultrasonic oscillator was used to equally scatter a certain amount of HO-CNTs. The aqueous solutions containing 10.0 gM and 21.5 g-F were heated to 70 degrees Celsius in 150 ml bottom flask at a rate of 350 revolutions per minute until the liquid

turned transparent. While we waited for this to occur, we added 50% triethanolamine aqueous solution to the HO-CNT water dispersion and gradually transferred it to the flask for pH adjustment to 8–9. To prepare a hydroxylated carbon nanotube-improved prepolymer solution of shell material, the reaction liquid was maintained at the specified temperature and mechanical stirring rate for 3.0 hours.

2.1.2. Phase-Change Material Esterification. Magnetic stirrers were used to mix SMA 1000HNa and water in a 250 ml beaker, which was heated to 75°C and covered with plastic film. Mechanically stirred and condensed n-hexadecanol was added to the flask, which was heated to 75°C in an oil bath, and the flask was stirred at a low rotating speed. It was then added to the core material in order to bring the temperature down to an even level. Forcefully emulsifying the solution at a velocity of 2000 revolutions per minute resulted in a stable oil-in-water (O/W) suspension. A 500 rpm stirring rate of citric acid aqueous solution maintained the pH of the emulsion system after 90 minutes. To prevent the emulsion from burning, the temperature was maintained at 65°C .

2.1.3. The Formulation of Enhanced MicroPCMs. This modified prepolymer solution, 9.6 grammes, was added to the n-hexadecanol in a drop-wise manner within 30 minutes after the temperature of the system had restored to 65 degrees Celsius. Shell prepolymers were polycondensed and cross-linked in a mixed environment at 70°C for 3.0 hours to produce the microcapsules. A vacuum-assisted membrane filter was used to separate the resulting suspension from the aqueous phase and allow it to cool to room temperature on its own. To create microcapsule powders, the microcapsule specimens were dehydrated in void oven at 50 degrees Celsius for 48 h after being rinsed three times with a warm 50-weight percent ethanol-water solution.

Similar to microPCM-0.0, a "blank" microcapsule sample was also created using the same methods, but with no inclusion of HO-CNTs. Each of the six microcapsules had a different proportion of hydroxylated carbon nanotubes comparative to the shell material: microencapsulated phase-change material—0.1, 0.2, 0.3, 0.4, and 0.6, correspondingly. As shown in Table 1, you may create microcapsules using modified nanocrystals and n-hexadecanol/melamine formaldehyde resin.

2.2. Properties and Evaluation. The chemical compositions of dried-out microencapsulated phase-change materials, n-hexadecanol, melamine formaldehyde resin, and hydroxylated carbon nanotubes were determined. The positive aspect of microencapsulation seems to be that the core material is entirely coated and confined from the outside enviro. 5 mg specimens were wrapped in an aluminium pan and verified in a N-atmosphere at temperatures ranging from zero to eighty degrees Celsius at a ten-degree-per-minute heating and cooling rate. In the course of testing, specimens start heating at 20°C to 80°C , detained at 80°C for 3 minutes, then air conditioned to 0°C , maintained at 0°C for 5 minutes, and again heated to 80°C .

TABLE 1: The experimental protocol for the fabrication of hydroxylated CNTs improved micro-phase-change materials.

Specimens	Emulsion system			Prepolymer system			
	n-Hexadecanol (g)	SMA 1000HNa (g)	Deionized water (ml)	Melamine (g)	Formaldehyde (g)	HO-CNTs (mg, wt%)	Deionized water (ml)
MicroPCM-0.0	14.5	2.9	100	12	22.1	0,0	25
MicroPCM-0.1	14.5	2.9	100	12	22.1	19, 0.1	25
MicroPCM-0.2	14.5	2.9	100	12	22.1	38, 0.2	25
MicroPCM-0.3	14.5	2.9	100	12	22.1	56, 0.3	25
MicroPCM-0.4	14.5	2.9	100	12	22.1	74, 0.4	25
MicroPCM-0.5	14.5	2.9	100	12	22.1	92, 0.5	25
MicroPCM-0.6	14.5	2.9	100	12	22.1	110, 0.6	25

For the NETZSCH Proteus investigation, the next heating and cooling DSC dashes were together after each sample was heated to completely destroy all thermal and processing histories of the materials being investigated. Energy storage efficiency (E), distinct as the mass ratio of PCM to total microcapsule mass, was determined using the following formula when microPCMs were synthesized:

$$E(\%) = \frac{\Delta H_{m,\text{microPCMs}} + \Delta H_{c,\text{microPCMs}}}{\Delta H_{m,n\text{-hexadecanol}} + \Delta H_{c,n\text{-hexadecanol}}} \times 100\%. \quad (1)$$

The constant-temperature heating plate was used to evaluate the thermal stabilization of microencapsulated phase-change materials. On the pad paper, we inserted the microPCMs and n-hexadecanol and heated them simultaneously. All of the samples were heated to 65°C for 0, 30, or 60 seconds before being photographed using a mobile camera. For this investigation, a C5465 probe was used with a hot disc thermal persistent examiner based on the transient plane source (TPS) approach. Using a 15 MPa press for 60 seconds, two cylindrical flat-surface blocks with 10 mm high and diameters of 10 mm each were produced from the powder samples. Afterwards, two cylindrical blocks were placed in between the probe and the blocks. At least three measurements were taken at room temperature for each sample, and the average value was computed and recorded. Thermal cycling tests using an alternate high-low temperature test chamber were used to assess microPCMs' thermal durability. The samples were heated to a temperature of 80 degrees Celsius over their melting point and subsequently cooled to a temperature of 0 degrees Celsius below their crystallization point. There were 500 cycles of the thermal cycling process. The PCM properties of microPCMs were calculated at the millimetre and micrometre scales. MicroPCM photothermal conversion performance may be measured with a self-built test system that contains a thermal isolation device, a sun simulator, and data gathering equipment, as previously

shown in our study. The solar emulator was powered by 300-watt sunlit energy, and data was gathered using T-type thermocouple junction sensors and a processor. It was utilized to record real-time temperature measurements of the sample cylinder block using a thermocouple probe with a quantity accurateness of 0.1°C and a procurement break of 1.0 s during the irradiation process.

3. Results and Discussion

It is possible that certain HO-CNTs may not be completely encased in the microcapsules, with a few of the ends protruding. For effective heat transmission external of microencapsulated phase-change material, the outwardly expanded hydroxylated carbon nanotubes of close microPCMs are physically linked together. The hydroxide groups on the surface of hydroxylated carbon nanotubes react with melamine formaldehyde resin prepolymer during shell creation, making them an excellent combination with microPCMs. The n-hexadecanol/melamine formaldehyde resin microcapsules' heat transfer rate is boosted by the movement of hydroxylated carbon nanotubes in and out of microencapsulated phase-change material. Table 1 contains the experimental technique for producing better microPCM using hydroxylated CNTs.

The abundant -OH functional groups of the HO-CNTs significantly interact with the prepolymer of melamine formaldehyde resin. With respect to absorption in the microPCM-0.6 spectrum, the moderate absorption peak at 1465 cm⁻¹ is classified as being part of the C-H stretching band. The 723 cm⁻¹ absorption peak is caused by the alkyl-(CH₂)_n-(n 4) group's in-plane rocking vibration band. The unusually sharp absorption peak at 1062 cm⁻¹ is caused by the main alcohol's C-O stretching vibration band. Captivation bands of the phase transition substance n-hexadecanol can be clearly seen in all of the vibration peaks. Parallel to this, the absorption peak at 813 cm⁻¹, which is a typical triazine skeleton vibration, is seen in the spectra of

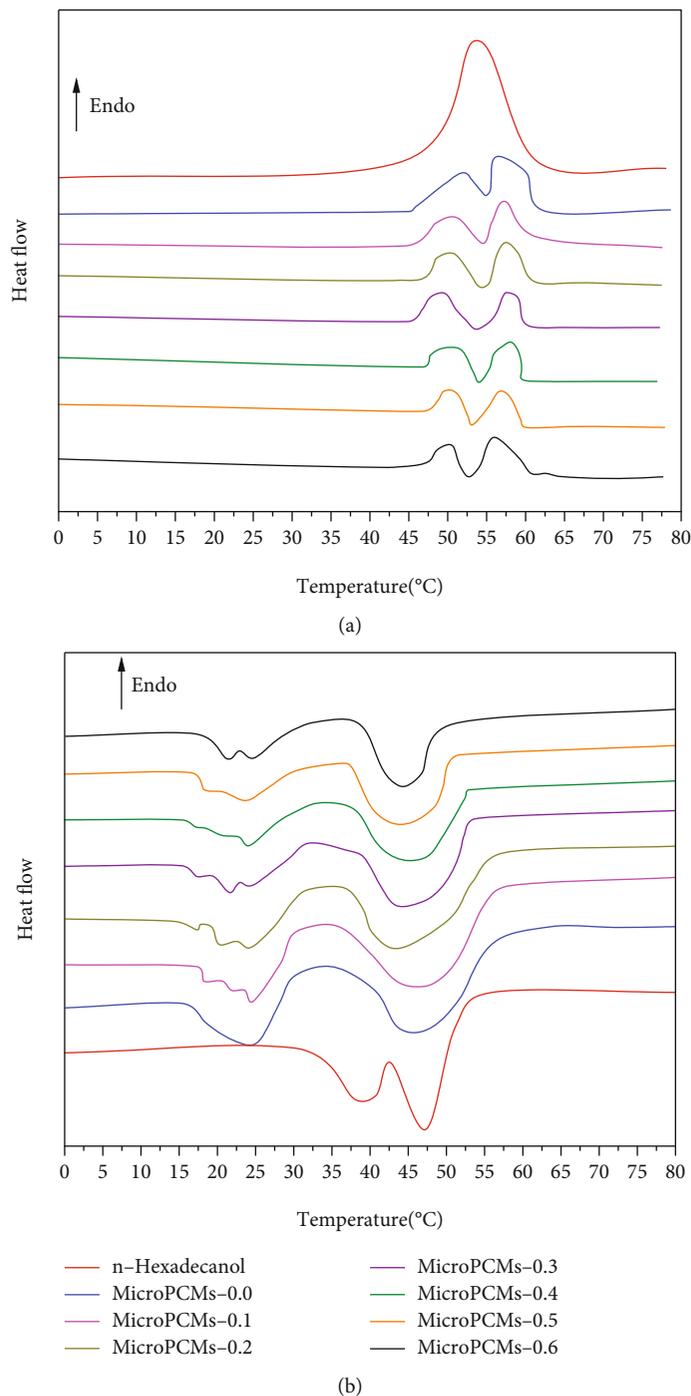


FIGURE 1: (a) The melting and (b) crystallizing processes in n-hexadecanol and microPCMs, respectively, as depicted by DSC curves.

microPCMs, together with the stretching vibrations at 1564 and 1350 cm^{-1} of the C--N and C-N groups. O-H and N-H stretching vibrations overlap, mostly owing to n-hexadecanol and MF resin, to produce wide absorbing ability at around 3330 cm^{-1} . Owing to the low loading of CNTs in microPCMs, HO-distinctive CNT's absorption peaks do not show up in their spectra. Based on spectral analysis, it was determined that the in situ polymerization of n-hexadecanol in MF resin was a success.

3.1. MicroPCM Thermal Storage Capability. When evaluating the microPCMs' heat storage properties in a real-world application, the PCM is critical. The DSC was therefore used to evaluate the microPCMs' phase change characteristics. There are DSC results for both unmodified microPCMs and modified microPCMs with varied quantities of HO-CNTs in Figure 1. While the melting process is shown by the upward endothermic peak in Figure 1(a), the crystallization process is shown by the downward exothermic peak

TABLE 2: Characteristics of the n-hexadecanol and microencapsulated PCM improved with hydroxylated carbon nanotubes in varied quantities.

Samples	Melting process				Crystallizing process					
	T_{mo} (°C)	T_{mp1} (°C)	T_{mp2} (°C)	ΔH_m (J/g)	T_{co} (°C)	T_{cp1} (°C)	T_{cp2} (°C)	ΔH_c (J/g)	ΔH (J/g)	E (%)
n-Hexadecanol	46.2	—	52.1	242.2	47.2	39.2	44.2	240.2	239.6	100.0
MicroPCM-0.0	37.1	43	52.1	183.6	48.5	30.1	44.6	179.8	179.4	73.8
MicroPCM-0.1	37.1	42.4	52.8	178.2	48.4	30.3	44.5	172.8	176.6	71.8
MicroPCM-0.2	38.1	42.9	52.5	183.6	48.6	32.4	44.8	180.4	179.8	74.6
MicroPCM-0.3	38.3	44.1	50.4	174.6	48.5	30.5	44.7	170.6	178.4	73.8
MicroPCM-0.4	38.2	43.6	53.3	170.1	48.6	30.7	44.5	166.6	164.3	71.4
MicroPCM-0.5	38.6	43.4	53.3	159.6	48.4	30.4	44.6	156.6	154.2	66.8
MicroPCM-0.6	38.7	41.8	52.2	158.5	48.6	28.6	44.7	154.9	152.2	63.8

(Figure 1(b)). Table 2 displays the samples' temperatures and latent heat values based on DSC analysis. The transition from a liquid to a hexagonal-filled solid phase is marked by two exothermic peaks, first at high temperature and next at low temperature. For thermal responsiveness and transfer, a lower melting temperature for microencapsulated n-hexadecanol appears to be advantageous due to the huge specific surface areas of microPCMs. The crystallization temperature of microencapsulated n-onset hexadecanol is substantially comparable to the temperature of pure n-hexadecanol. As can be shown in Figure 1, the peak of crystallization at the solid-phase transition for microPCMs moves to a lower temperature range (Figure 1(b)). Because the molecular formation of n-hexadecanol restrained, this resulted in a restricted crystallization behaviour during the freezing process. During the phase shift, the peak area of microPCMs is also shown to be smaller than that of pure n-hexadecanol. For the generation of microPCM phase-change enthalpy in the core shell, only n-hexadecanol may undergo the requisite phase changes.

MicroPCM-0.0 and pure n-hexadecanol both have average enthalpy values of $180.5 \text{ J}\cdot\text{g}^{-1}$, as seen in Table 2. It has also been shown that the phase transition enthalpy of microPCMs decreases as the HO-CNT dose is increased. Whereas the hydroxylated carbon nanotube dose is <0.2 weight percent, the specific heat of microencapsulated phase-change materials is practically constant at $180 \text{ J}\cdot\text{g}^{-1}$ with an equivalent energy storing efficacy of roughly 75%. This suggests that HO-CNT dosages below 0.2 wt percent have no impact on the specific heat of microencapsulated phase-change materials. In the aqueous solution, the HO-CNTs diffused efficiently due to the abundance of $-\text{OH}$ groups on their surface at low additions. Thus, the n-hexadecanol core material may be further encapsulated by the HO-CNTs interacting fully with the MF resin prepolymer. MicroPCM latent heat decreases more slowly when the HO-CNT dose is more than 0.2%. This is in accord with experimental outcome stated in the analysis. As a result, it may be possible to hasten the polycondensation of the MF resin prepolymer in order to release the partial shell materials from their packaging with n-hexadecanol, thereby allowing the HO-CNTs to be dispersed. For the microPCMs to lose their latent heat, an excessive amount of HO-CNTs

must be supplied. H and E are greatly enhanced to 155.7 J/g and 64.52 percent when the HO-CNT dosage is increased to 0.6 percent when microPCMs are used as the energy storage. Because of their apparent capacity to store substantial amounts of heat and energy at low temperatures and their precise phase transition temperature, n-hexadecanol/melamine formaldehyde resin microcapsules treated with HO-carbon nanotubes may be able to store thermal energy. Characteristics of n-hexadecanol and microencapsulated phase-change materials are shown in Table 2.

3.2. Thermal Stabilization of Microencapsulated PCMs. A variety of hydroxylated CNT-filled microPCMs were tested for thermal stability using thermal analysis methodologies in this section. MF resins and microPCMs are shown in Figures 2(a) and 2(b) for the thermogravimetric tests of n-hexane. Table 3 shows the measurement results. At a temperature of 5% weight loss, microPCMs begin to lose weight owing to a little quantity of water and inadequate reactants in the specimens (T_5 percent). At 300°C , microPCMs lose $W_{300^\circ\text{C}}$ and $W_{165^\circ\text{C}}$ of their total weight. The mass % of core materials in microencapsulated phase-change materials can be estimated by subtracting the weight reduction of residual water and imperfect reactants from $W_{300^\circ\text{C}}$ to $W_{165^\circ\text{C}}$.

MicroPCMs remain in a very stable, dry powder state even at temperatures considerably beyond the melting point of n-hexadecanol (50°C), even during the heating process. Due to the microPCMs' absence, n-hexadecanol/MF resin microcapsules are form stabilized, whether or not they include HO-CNTs. An effective barrier to leakage is provided by the resin, which is made up of polymethylmethacrylate (MF). Thermogravimetric methods were used to analyze N-hexadecanol, MF resins, and microPCMs at temperatures between 50 and 750 degrees Celsius. Pure n-hexadecanol has a starting weight loss temperature (T_1 percent) of 146°C , and by 300°C , there are almost no residues left owing to the evaporation of molten N-hexadecanol. There is just one stage of weight loss. Temperature increases cause the MF shell to slowly and steadily lose mass. Adsorbed water, remaining reactants, and oligomers lose weight at temperatures below 300°C owing to volatility and breakdown, while at temperatures between 300°C and

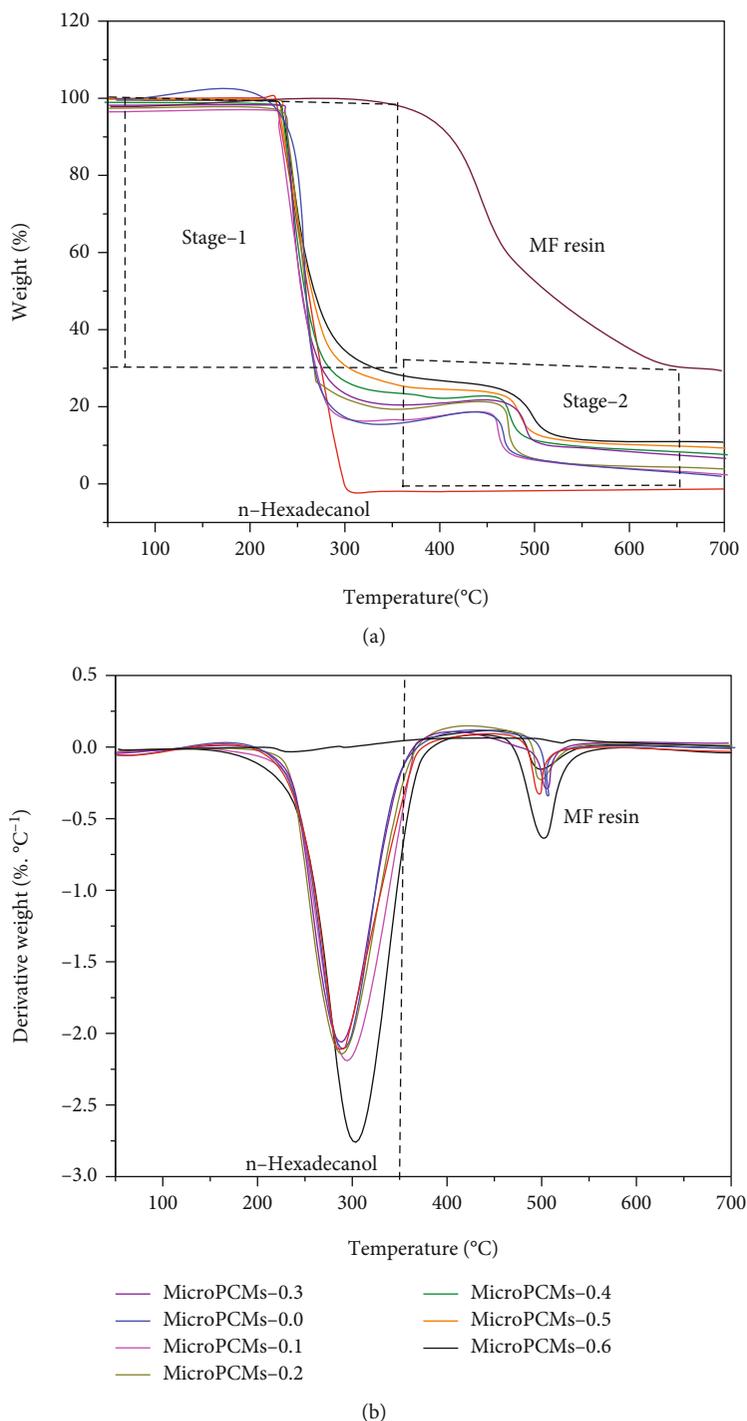


FIGURE 2: MicroPCMs and n-hexadecanol modified with various concentrations of HO-CNTs are shown in (a) TGA and (b) DTG curves.

600°C, the MF shell undergoes significant pyrolysis. The pyrolysis of MF resin at temperatures of 300–600°C is mostly responsible for the first step, whereas the evaporation of n-hexadecanol, the core material, is primarily responsible for the second stage. As indicated in Table 3, micro-phase-change material improved with various quantities of HO-carbon nanotubes had almost identical beginning weight loss temperatures (T_5 percent) at 165°C, indicating that

these microPCMs may be effectively used at temperatures lower than 165°C without degrading in performance. Calculated core mass percentages are essentially compatible with energy storage efficacy of micro-phase-change materials from DSC analysis. Microencapsulated phase-change materials modified with high n-hexadecanol n-hexadecanol mass % HO-CNTs may be employed in a wide range of practical sectors with operating temperatures below 165°C, as

TABLE 3: Thermo gravimetric results of the micro-phase-change materials improved with various quantities of HO-carbon nanotubes.

Samples	$T_{5\%}$ ($^{\circ}\text{C}$)	W_{300-C} (%)	$W_{300-C} - W_{165-C}$ (%)
MicroPCM-0.0	167	81.07	76.04
MicroPCM-0.1	165	75.76	70.81
MicroPCM-0.2	167	83.61	80.12
MicroPCM-0.3	167	75.87	71.87
MicroPCM-0.4	165	75.35	70.42
MicroPCM-0.5	167	72.86	64.72
MicroPCM-0.6	165	69.73	66.12

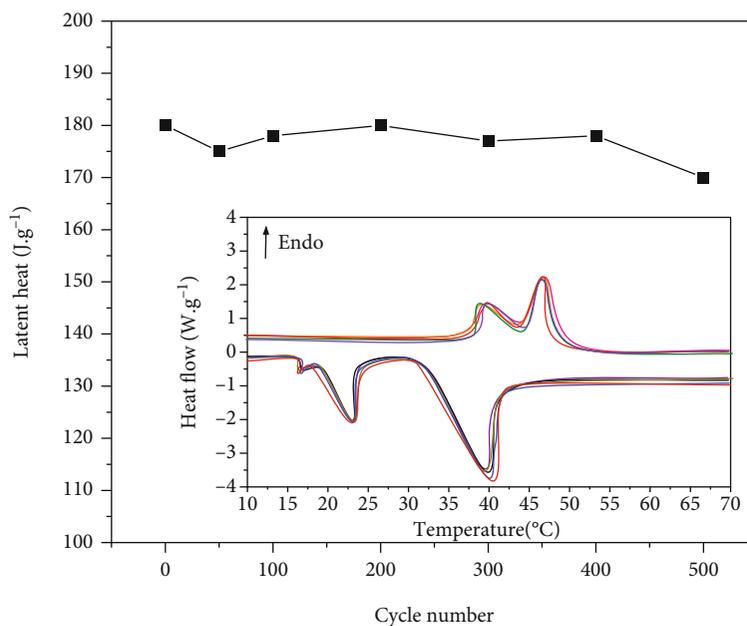
demonstrated by this study. Results on the enhanced micro-phase-change materials with different amounts of HO-carbon nanotubes are shown in Table 3.

3.3. Thermal Conduction of the Microencapsulated Phase-Change Materials. Thermal conduction is an important property that moves the thermal responsiveness to fascination and removal of PCM enthalpy in microPCM thermal energy storage. These microcapsules' heat transmission capabilities were evaluated by measuring the thermal conduction of the n-hexadecanol/melamine formaldehyde resin with varying quantity of hydroxylated CNT additives. The impact of the hydroxylated carbon nanotube fillings on microPCMs' thermal conduction was also examined and conversed in this study. There is a noticeable enhancement in the thermal conduction of microPCMs when HO-CNTs are added to varied degrees. The unmodified microPCMs have a measured thermal conductivity of just $0.3002 \text{ Wm}^{-1}\cdot\text{K}^{-1}$ due to the weak thermal conduction of natural PCMs and polymeric shells. When HO-CNTs are included in microPCMs, the resulting increase in thermal conductivity is 0.1 weight percent or $0.3181 \text{ Wm}^{-1}\cdot\text{K}^{-1}$. When HO-CNTs are introduced at a weight percentage of 0.6, micro-phase-change materials have the extreme thermal conduction of $0.3597 \text{ Wm}^{-1}\cdot\text{K}^{-1}$. The accumulation of HO-carbon nanotubes considerably boosted the thermal conduction of the n-hexadecanol/melamine formaldehyde resin microcapsule, demonstrating that the microPCM heat incriminating/discharging rate was successfully raised. HO-CNTs may help reduce interfacial heat resistance by creating a bond with the melamine formaldehyde resin shell due to their high aspect ratio and many hydroxylated groups on the outer surface. Additional HO-CNTs, which adhere to the microPCM shell, form thermal conductors between microPCMs and increase the transfer rate of heat between them. After adding HO-carbon nanotubes to the carbon nanotubes, n-hexadecanol/melamine formaldehyde resin microcapsules exhibit a considerable increase in thermal conductivity and keep that level even at a modest accumulation, hence increasing its thermal responsiveness to changes in temperature.

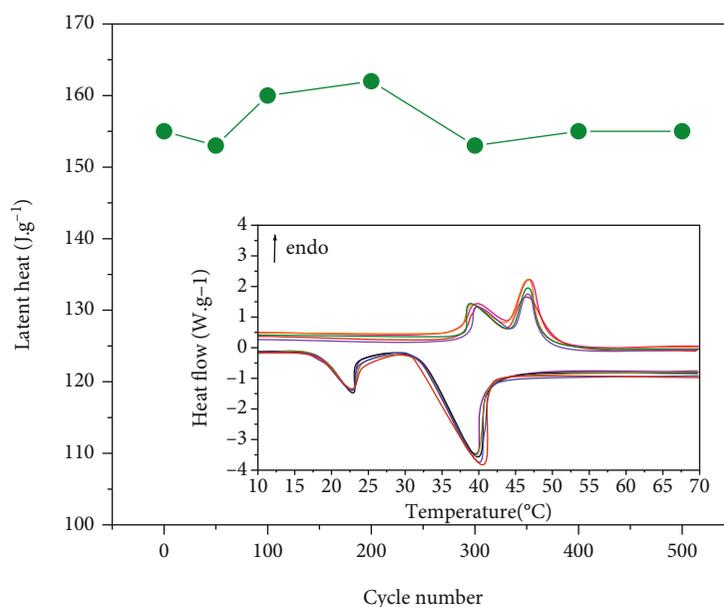
3.4. MicroPCM Thermal Cycle Testing. A 500-cycle thermal cycling experiment was directed to test the thermal consis-

tency of the microPCM-0.0 and microPCM-0.6 that were created. First, fifty-fifth, one hundredth, two hundredth, three hundredth, four hundredth, and five hundredth minutes of melting and crystallizing DSC curves of microPCM-0.0 and 0.6. Next 500 heat cycles, the MicroPCM-0.0's phase change behaviour remains largely constant, but the MicroPCM-0.6's peak phase change profile deviates slightly from the primitive state. Although it is still possible that microPCM-0.6 has a slight departure from its primordial condition, its latent heats at the 500th thermal cycle have been shown to be almost identical to those of microPCM-0.0 and microPCM-0.6. Figures 3(a) and 3(b) are the microPCM-0.0 average latent heat (H), and the microPCM-0.6 latent heat values for microPCM-0.0 and 0.6 were found in this study to be roughly the same as their initial values of $180.5 \text{ J}\cdot\text{g}^{-1}$ at 500 cycles of thermal cycling. During repeated heating and cooling cycles, this material does not leak at all. Since the formaldehyde resin encapsulates n-hexadecanol, it is safe to use. The addition of HO-carbon nanotubes has no effect on the PCM cycling behaviour of n-hexadecanol/MF resin microcapsules. For thermal storage applications, the improved microPCMs have excellent thermal dependability due to the incorporation of HO-CNTs.

3.5. The MicroPCMs' Photothermal Conversion Performance. A variety of PCMs with varied levels of enhanced photothermal conversion capability were found to be useful for storing plentiful renewable solar energy based on the literatures that were reviewed. The MF resin and microPCMs were monitored for temperature changes under continuous simulated solar irradiation in terms to assess the impact of HO-CNT inclusion on the photothermal conversion property. The HO-carbon nanotube-improved microPCMs display a comparable heat change mechanism as the unmodified microPCMs when the irradiation period is extended. During irradiation, the temperature of microPCMs increases at an accelerated rate, which is solely dependent on their sensible heat. When irradiated for extended periods of time at temperatures between 40 and 50 degrees Celsius, it is clear that the heat rise degree of microPCMs is slower than that of the MF resin, leading to the formation of a temperature buffer zone, as indicated by the grey-dotted box. n-Hexadecanol microcapsulated in resin shell undergoes solid-liquid phase change as temperature increases, and this is why this phenomena happens. As a result, microPCMs absorb a significant quantity of solar energy and convert it into latent heat. Immediately after melting the n-hexadecanol core material over 50°C , microPCMs must be immediately elevated to the maximum balanced temperature by imitating solar irradiation. For solar thermal storage, unaltered microPCMs maintain a longer buffer at $40\text{--}50^{\circ}\text{C}$ for around 1000 seconds than the HO-CNT-modified microPCMs. When bombarded for an extended period of time, HO-CNT-modified microPCMs have a higher temperature than untreated microPCMs. Filling microPCMs with more HO-CNTs resulted in higher temperatures when heated in the same irradiation setting. Consequently, when irradiation has achieved equilibrium, microPCMs without



(a)



(b)

- 1st cycle
- 50th cycle
- 100th cycle
- 200th cycle
- 300th cycle
- 400th cycle
- 500th cycle

FIGURE 3: The next 500 thermal cycles and the latent heat of the microencapsulated phase-change materials. (a) 0.0 and (b) 0.6.

HO-CNT additions rise from 28 to 64.0°C in temperature, whereas those with 0.1 and 0.06 percent HO-CNT additions rise from 66.0 to 75.0°C, and it is shown in Figure 4. Due to the strong optical absorption capability of the filler HO-CNTs, the temperature of microPCMs modified with filler HO-CNTs rises significantly. For photothermal energy storage, the microPCMs' temperature buffer of 40 to 50°C is sufficient even at a HO-CNT dosage of 0.6 weight percent.

According to the results of this study, all modified microPCMs exhibit stable photovoltaic translation behaviour in solar energy absorption and release. Filler HO-CNTs may significantly increase the photothermal transition efficiency of n-hexadecanol/melamine formaldehyde resin microcapsules with maximum thermal storing capacity, thereby making microPCMs an attractive alternative for use in solar energy storage cells such as the DC-DASC.

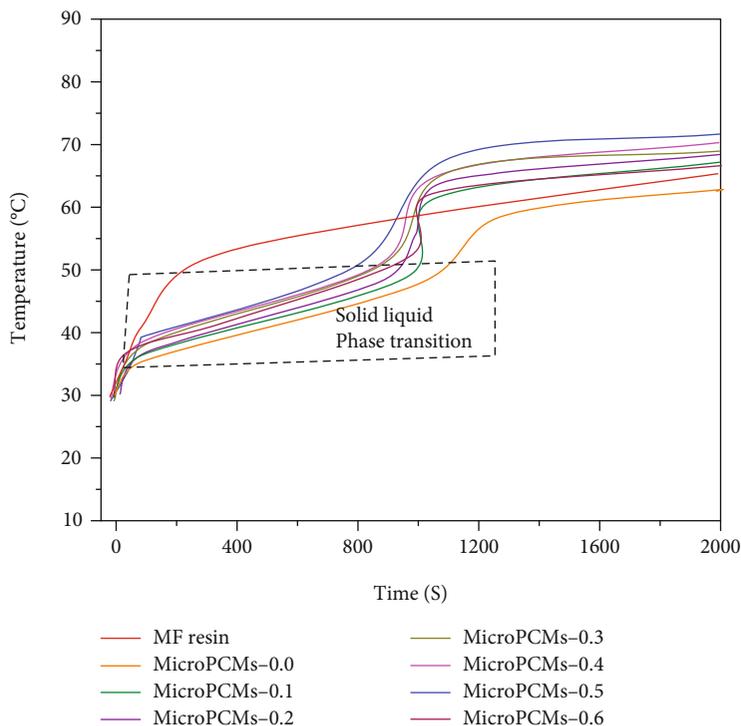


FIGURE 4: Irradiation time affects both the MF resin and microPCMs' temperature curves.

4. Conclusions

A sequence of hydroxylated CNT-improved microencapsulated phase-change materials with n-hexadecanol cores and melamine formaldehyde resin shells were effectively constructed in this work using in situ polymerization. On the microPCMs' surfaces, there are many HO-CNTs that can be observed. DSC observations from microPCM microparticles show that after the quantity of hydroxylated carbon nanotubes is improved, the latent heat decreases. It is found that the energy storage efficiency of microPCMs at 0.2 weight percent HO-CNTs is 75.25% and the corresponding melting and latent heat temperatures are 51.5°C. After adding an additional 0.6% of HO-CNTs, the average latent heat of the microPCMs stays at 155.6 J·g⁻¹·°C and 181.5 J⁻¹. This study shows that microPCMs modified with different levels of HO-CNT have excellent thermal stability and form stability throughout the phase shift process. The addition of HO-CNTs to microPCMs has considerably enhanced the thermal conductivity and photothermal conversion efficiency. More light-responsive temperatures were seen in the modified microPCMs than in the unmodified microPCMs, with a maximum thermal conduction of 0.3597 Wm⁻¹·K⁻¹ and an increase in light-responsive temperature in simulated sunshine. The HO-carbon nanotube-improved n-hexadecanol/melamine formaldehyde resin microcapsules with remarkable photothermal conversion properties, high PCM, and appealing thermal charging/discharging rate are promising materials for solar energy storage.

Data Availability

The data used to support the findings of this study are included within the article. Further data or information is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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