Characteristics of phase-change materials containing oxide nano-additives for thermal storage

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Abstract
In this study, the authors report the production of nanocomposite-enhanced phase-change materials (NEPCMs) using the direct-synthesis method by mixing paraffin with alumina (Al₂O₃), titania (TiO₂), silica (SiO₂), and zinc oxide (ZnO) as the experimental samples. Al₂O₃, TiO₂, SiO₂, and ZnO were dispersed into three concentrations of 1.0, 2.0, and 3.0 wt.%. Through heat conduction and differential scanning calorimeter experiments to evaluate the effects of varying concentrations of the nano-additives on the heat conduction performance and thermal storage characteristics of NEPCMs, their feasibility for use in thermal storage was determined. The experimental results demonstrate that TiO₂ is more effective than the other additives in enhancing both the heat conduction and thermal storage performance of paraffin for most of the experimental parameters. Furthermore, TiO₂ reduces the melting onset temperature and increases the solidification onset temperature of paraffin. This allows the phase-change heat to be applicable to a wider temperature range, and the highest decreased ratio of phase-change heat is only 0.46%, compared to that of paraffin. Therefore, this study demonstrates that TiO₂, added to paraffin to form NEPCMs, has significant potential for enhancing the thermal storage characteristics of paraffin.

Keywords: Alumina, Nanocomposite-enhanced phase-change materials, Paraffin, Silica, Titania, Zinc oxide

Background
Thermal energy storage (TES) by solar power has become a popular research topic in recent years. Because of the impact of day and night on solar thermal energy storage, thus, the development of efficient energy storage materials will directly influence the utilization efficiency of solar thermal energy storage [1-3]. In general, single-phase thermal energy storage materials require a large storage space, which reduces the usefulness of thermal storage [4,5]. Therefore, developmental research on thermal energy storage materials focuses on phase-change materials (PCMs), and several research results and practical applications have been published [6-10].

Most PCMs have low thermal conductivity, which prevents them from overcoming problems of rapid load changes in the charging and discharging processes [11]. To overcome this obstacle and to obtain excellent thermal properties, studies have proposed various techniques for enhancing the thermal conductivity of PCMs, such as adding metallic or nonmetallic particles with high thermal conductivity [12-15], inserting fins [16-18], incorporating porous or expanded materials [19-27], inserting fibrous materials [28-31], and incorporating macro-, micro-, and nano-capsules [32-34]. The above-mentioned methods for enhancing the thermal conductivity of PCM involve adding high-conductivity materials to improve the thermal conductivity of PCMs as the most simple and feasible method.

Metals have excellent thermal conductivity; therefore, they can be expected to enhance the thermal conductivity of PCMs significantly. However, metal materials oxidize, and their application to PCMs can degenerate and reduce the thermal conductivity of PCMs in the long run. Although adding metal oxides or minerals to PCMs to enhance thermal conductivity is worth considering, the thermal conductivity of such additives must be higher than that of the PCM if they are to enhance the thermal conductivity of PCMs. Moreover, a poor combination of additives to PCMs can increase interface
thermal resistance and sedimentation and reduce the performance of the thermal storage without enhancing the thermal conductivity of PCMs. With the development of nanotechnology, the size of the additives can be reduced to a nanometer scale, and the reduced size can enhance the suspension performance, specific surface area, and heat transfer performance of the additives. In previous studies, carbon nanotubes (CNTs) [35-37], carbon nanofibers (CNFs) [37,38], Al2O3 nanoparticles [39-41], and Ag nanoparticles [42] were added to form nanocomposite-enhanced phase-change materials (NEPCMs) as a technique to enhance the thermal performance of PCMs. However, CNTs, CNFs, and Ag are expensive; therefore, the extensive use of these nanoparticles can reduce the economic benefits of PCMs for TES.

Paraffin is a material of low cost and toxicity that can be decomposed by bacteria. Therefore, it was chosen as the PCM thermal storage material for this study. Furthermore, the melting point of paraffin is approximately 55°C to 65°C, which makes it suitable for thermal storage in non-concentrating solar collectors. The direct-synthesis method was used to produce NEPCMs by adding alumina (Al2O3), titania (TiO2), silica (SiO2), and zinc oxide (ZnO) to paraffin. To demonstrate the feasibility of using NEPCMs in thermal storage systems, both the heat conduction and differential scanning calorimeter (DSC) experiments were used to assess the characteristics of NEPCMs and paraffin.

Methods
Preparation of NEPCMs
Fully refined paraffin (Choneye Pure Chemicals, Taipei, Taiwan) served as the base material in this study. Commercial Al2O3 (AI-13P, Yong-Zhen Technomaterial, Taipei, Taiwan), TiO2 (P-25, Degussa, Düsseldorf, Germany), SiO2 (Si-30P, Yong-Zhen Technomaterial), and ZnO (Zn-30, Yong-Zhen Technomaterial) were used to modify the paraffin. Figures 1, 2, 3, and 4 show the transmission electron microscope (TEM; H-7100, Hitachi, Tokyo, Japan) and field-emission scanning electron microscope (FE-SEM; LEI 1530, Zeiss, Oberkochen, Germany) images of Al2O3, TiO2, SiO2, and ZnO, respectively. The particle size distribution of Al2O3, TiO2, and SiO2 was approximately 20 to 30 nm, and the particle size distribution of ZnO was in the range of several hundred nanometers.

The additives were combined with paraffin to produce NEPCMs. NEPCMs produced by direct-synthesis method were used to disperse the additives in the paraffin into three weight fractions (1.0, 2.0, and 3.0 wt.%), which formed the experimental samples in this study. The liquid paraffin was then stirred continuously at 120°C using an electromagnetic stirrer/hot plate (PC420D, Corning Inc., Corning, NY, USA). The additives were added to the liquid paraffin divided by several times until the mixtures reached the desired concentration. The liquid NEPCMs were continuously homogenized for 40 min at 120°C using a high-speed homogenizer (T25 digital, IKA, Stanfen, Germany) at 6,000 rpm to evenly disperse the additives in the liquid paraffin. The liquid NEPCMs were then dispersed at 90°C for 1 h using an ultrasonic bath (D400H, TOHAMA, Hsinchu, Taiwan) to complete the synthesis of NEPCMs. Based on our past...
experience, the three dispersion devices have their own advantages and features. Interactive use of these machines can prevent the temperature of the devices from rising, and good dispersion of NEPCMs can be achieved in a shorter period.

The melted NEPCMs were poured into glass test tubes (30 cc) and allowed to cool and solidify. A spectrometer (BRC112E, B&W Tek, Newark, DE, USA) with an integrating sphere was used to test reflectivity of NEPCMs at 600 nm in the upper and lower parts (distance 12 cm) of the test tubes. A small difference in reflectivity between the upper and lower parts of the test tube indicates a high suspension performance of the additive suspended in the paraffin. In this study, the difference in reflectivity between the upper and lower parts of the test tube with an NEPCM must be less than 5% for the NEPCM to qualify as an experimental sample. The reflectivity difference of NEPCMs with Al₂O₃, TiO₂, SiO₂, and ZnO were 1.8%, 1.9%, 3.0%, and 3.9%, respectively.

Experimental procedure and analysis

Heat conduction experiment

This study investigates the effects of additives on temperature difference at a fixed location based on the paraffin to evaluate the heat conduction performance. The temperature difference of the experimental samples in steady state is lower, which represents the samples with higher heat conduction performance and thermal conductivity. Figure 5 shows the test apparatus used for the heat conduction performance of NEPCMs. The 40 g of melting, uniformly dispersing paraffin and NEPCMs was poured into a polypropylene test tube and then was cooled and solidified in an isothermal bath (P-20, YSC, Hsinchu, Taiwan) at 25°C to complete a unit of sample
for the heat conduction experiment. Two thermocouples were installed on all test samples, and the temperature change was recorded by a data logger (TRM-20, TOHO, Kanagawa, Japan). Another isothermal bath (P-10, YSC) was stabilized to a test temperature (70°C, 75°C, 80°C, and 85°C), and the sample was then placed into the isothermal bath. The measurement time was 90 min for each sample, and the average temperature data during the last 10 min was referred to as a steady temperature. The steady-state temperature difference of the thermocouple was the steady-state temperature difference ($T_d$) of the test samples.

**DSC experiment**

To select the proper PCMs, we must consider the suitable phase-change temperature and phase-change heat for the different temperatures of the heat sources and practical application. DSCs are often used to determine the phase-change temperature and phase-change heat of PCMs [23,25,31-33,37]. A DSC (Q20, TA, New Castle, DE, USA) with a vapor compression refrigeration cooling system (RCS40, TA) was used in the charging and discharging experiments in this study to assess the melting and solidification temperatures and the phase-change heat of the samples. The experimental temperature range was 25°C to 90°C at a fixed heating and cooling rate of 4.0°C/min. The calorimetric precision and temperature accuracy of the DSC were ±0.1% and ±0.1°C, respectively. The test samples were taken by a quantitative dropper after the NEPCMs were melted and stirred evenly using an electromagnetic stirrer/hot plate. Each sample was placed in an aluminum sample pan (Tzero pan, no: T100915) with a lid (Tzero hermetic lid, no: T100624), and the DSC experiment was conducted under high-purity nitrogen (5N) atmosphere. In this experiment, the sample's weight was controlled at 5.0 ± 1.5 mg in the sample pan using a precision electronic balance (XS-125A, Precisa, Dietikon, Switzerland) at a precision of 0.1 mg. The thermograms of the DSC charging and discharge experiments were analyzed by a computer software (Universal Analysis 2000, TA) and at a temperature ranging from 30°C to 70°C to calculate the phase-change latent heat for all the samples. Comparing the experimental results of DSC for NEPCMs with the paraffin under the same experimental parameters shows the effects of the additives on the melting and solidification temperatures and the heat of the paraffin.

**Experimental data analysis**

To compare the experimental data after adding the additives to paraffin ($D_a$), all data obtained with the paraffin were gathered to form baseline values ($D_p$). The experimental data obtained from the NEPCMs were compared with the baseline values. The differences before and after adding the additives to the paraffin are presented as percentage ($R$), and calculated as follows:

$$ R = \left( \frac{D_a - D_p}{D_p} \right) \times 100\% $$

**Results and discussion**

In Figure 6, the $R_{Td}$ of NEPCMs with Al$_2$O$_3$, TiO$_2$, SiO$_2$, and ZnO at both different concentrations (1.0, 2.0, and 3.0 wt.%) and test temperatures (70°C, 75°C, 80°C, and 85°C) shows a $T_d$ lower than that of paraffin. The $T_d$ of the experimental samples in steady state is lower, which represents the samples with higher heat conduction performance or thermal conductivity based on heat conduction theory. Experimental results show that adding these additives to the paraffin can really improve the thermal conduction performance (or thermal conductivity) of the paraffin, and adding TiO$_2$ to the paraffin is the optimal selection. The NEPCMs can enhance the thermal conduction performance of the paraffin mainly because these additives have higher thermal conductivity as well as movement of additives in liquid paraffin to cause the quasi-convection phenomenon. Although the additives have similar thermal conductivity, the enhanced heat conduction performance of NEPCMs is obviously different mainly due to both the suspension performance of additives in paraffin and the combination performance between the additives and paraffin. The maximum decreased ratio of $T_d$ is 63.3% at 75°C by adding TiO$_2$ of 3.0 wt.% into the paraffin. Adding those additives to paraffin results in a higher heat conduction performance and allows the

![Figure 6 Temperature difference ratio of the NEPCMs.](image-url)
NEPCMs to response the rapid heat load changes in the charging and discharging process.

Figures 7, 8, and 9 present the DSC thermograms of the NEPCMs with different additives and concentrations of additives. The phase-change latent heat for calculation ranges from 30°C to 70°C. As shown in the figures, during the melting and solidification process, the phase-change peak ($T_p$) was 60.74°C and 58.68°C, the onset temperature ($T_o$) was 54.00°C and 60.64°C, and the latent heat of phase change was 199.4 and 194.5 kJ/kg for paraffin, respectively. Because the paraffin was not a pure substance, its melting and solidification ranges were wider, compared to those of the pure substance. Furthermore, adding different additives at varying concentrations alters the endothermic and exothermic curve. The additives decreased the endothermic and exothermic peak and delayed the end of the melting point of the phase change. Table 1 shows the DSC experimental results of the NEPCMs for the melting and solidification processes with different additives and additive concentrations. To compare the effects of the charge and discharge characteristics of NEPCMs with different additives and additive concentrations, the data in Table 1 is further calculated as ratios by Equation 1 and are plotted in Figures 10, 11, 12, 13, 14, and 15.

Figures 10, 11, 12, 13, 14, and 15 show the ratio of the melting onset temperature ($T_{mo}$), melting peak temperature ($T_{mp}$), solidification onset temperature ($T_{so}$), solidification peak temperature ($T_{sp}$), melting heat ($H_m$), and solidification heat ($H_s$) of the NEPCMs, respectively, as calculated by the experimental results. These experimental results show the differences between the NEPCMs and paraffin.

Figure 10 shows the $R_{T_{mo}}$ of NEPCMs with Al$_2$O$_3$, TiO$_2$, SiO$_2$, and ZnO at concentrations of 1.0, 2.0, and 3.0 wt.%. A low $T_{mo}$ in the NEPCMs allows the melting phase change to occur at a low temperature. In practical applications, this means that the melting phase change of NEPCMs can occur at a heat source with a relatively low temperature. Increasing the amount of Al$_2$O$_3$ and TiO$_2$ in the paraffin reduces the $T_{mo}$ of the paraffin, and increasing the amount of SiO$_2$ and ZnO in the paraffin increases the $T_{mo}$ of the paraffin. For NEPCMs with Al$_2$O$_3$ and TiO$_2$ at concentrations of 1.0, 2.0, and 3.0 wt.%, the $T_{mo}$ ratio decreased by 0.91%, 0.72%, and 0.54% and by 1.33%, 1.13%, and 0.85%, respectively. Adding the Al$_2$O$_3$ and TiO$_2$ to the paraffin to form NEPCMs has better modification efficiency base on the test results of $T_{mo}$ but increasing the concentration of SiO$_2$ and ZnO will result in lower efficiency for lowering the $T_{mo}$. Figure 11 shows the $R_{T_{mp}}$ ratio of NEPCMs with Al$_2$O$_3$, TiO$_2$, SiO$_2$, and ZnO at concentrations of 1.0, 2.0, and 3.0 wt.%. Increasing the amount of Al$_2$O$_3$, TiO$_2$, and SiO$_2$ can increase the $T_{mp}$ of paraffin; however, increasing the amount of ZnO will not necessarily increase the $T_{mp}$ of paraffin. The instability of the $T_{mp}$ in the NEPCMs with ZnO is mainly a result of the larger particle size of ZnO, combination of the ZnO and paraffin, and poor suspension performance of ZnO in paraffin. Adding Al$_2$O$_3$, TiO$_2$, and SiO$_2$ to the paraffin resulted in a higher $T_{mp}$ and allowed a melting phase-change peak of the paraffin to occur at higher temperatures.

In Figure 12, the $R_{T_{so}}$ of the NEPCMs with Al$_2$O$_3$, TiO$_2$, SiO$_2$, and ZnO at concentrations of 1.0, 2.0, and 3.0 wt.% shows a $T_{so}$ higher than that of paraffin. The maximum enhanced ratio of $T_{so}$ is 1.8% by adding ZnO of 2.0 wt.% into paraffin. Adding those additives to paraffin resulted in a higher $T_{so}$ and allowed the solidification phase change of paraffin to occur at higher temperatures. This situation makes it possible to use a phase-change heat at higher temperatures to enhance the heat release rate of paraffin. Figure 13 shows the $R_{T_{sp}}$ of the NEPCMs with Al$_2$O$_3$, TiO$_2$, SiO$_2$, and ZnO at concentrations of 1.0, 2.0, and 3.0 wt.%. The effect of
adding Al₂O₃ and TiO₂ on $T_{sp}$ is not obvious; however, adding SiO₂ and ZnO to paraffin resulted in a lower $T_{sp}$ and allowed a solidification phase-change peak of paraffin to occur at higher temperatures.

The $R_{Hm}$ of the NEPCMs with Al₂O₃, SiO₂, and ZnO at concentrations of 1.0, 2.0, and 3.0 wt.% showed $H_m$ lower than that of paraffin, but adding TiO₂ to paraffin did not noticeably change the $H_m$, compared to that of paraffin (Figure 14). The experimental results of $H_s$ were similar to those for $H_m$. Figure 15 shows that adding TiO₂ to paraffin produced a minimal impact for $H_s$. In the cases of both the $H_m$ and $H_s$, adding TiO₂ decreased the phase-change heat of paraffin by less than 0.46%.

All experimental samples were tested for their suspension and combination performance with a spectrometer to confirm that the difference in reflectivity between the upper and lower parts of the test tube was less than 5%. During this process, the reflectivity differences of the NEPCMs with Al₂O₃ and TiO₂ were below 2.0%, whereas the reflectivity differences of the NEPCMs with SiO₂ and ZnO were above 3.0%. The NEPCMs with ZnO showed the lowest suspension performance, with a maximum reflectivity difference at 3.9%. Poor suspension performance of additives in paraffin cannot effectively enhance the heat conduction performance of NEPCMs due to sedimentation and uneven distribution of additives. Poor combination of additives with paraffin will produce a thicker interface layer to increase the interface thermal resistance between the paraffin and additives. This interface layer cannot contribute to the phase-change heat because phase change does not occur in the interface layer in the experimental temperature range, but it will reduce the unit volume of the thermal storage. In addition, the thicker thermal resistance layer also reduces the heat conduction performance of the NEPCMs. Furthermore, the thicker thermal resistance
| Samples          | Additive concentration (wt.%) | Process | Phase-change temperature (°C) | Latent heat (kJ/kg) |
|------------------|-------------------------------|---------|-------------------------------|--------------------|
|                  |                               |         | $T_s$                         | $T_p$              |
| Paraffin (P)     |                               | Charging| 54.00                         | 60.74              | 199.4             |
|                  |                               | Discharging| 60.64                         | 58.68              | 194.5             |
| P + Al$_2$O$_3$  | 1.0                           | Charging| 53.51                         | 61.18              | 197.9             |
|                  |                               | Discharging| 61.51                         | 58.68              | 191.2             |
|                  | 2.0                           | Charging| 53.61                         | 61.17              | 194.6             |
|                  |                               | Discharging| 61.61                         | 58.71              | 189.5             |
|                  | 3.0                           | Charging| 53.71                         | 61.11              | 184.2             |
|                  |                               | Discharging| 61.54                         | 58.52              | 179.9             |
| P + TiO$_2$      | 1.0                           | Charging| 53.28                         | 61.19              | 200.6             |
|                  |                               | Discharging| 61.56                         | 58.64              | 193.9             |
|                  | 2.0                           | Charging| 53.39                         | 61.00              | 200.1             |
|                  |                               | Discharging| 61.51                         | 58.77              | 194.0             |
|                  | 3.0                           | Charging| 53.54                         | 61.00              | 198.7             |
|                  |                               | Discharging| 61.53                         | 58.59              | 193.6             |
| P + SiO$_2$      | 1.0                           | Charging| 55.50                         | 61.1               | 185.6             |
|                  |                               | Discharging| 61.64                         | 58.15              | 180.0             |
|                  | 2.0                           | Charging| 56.62                         | 62.18              | 180.4             |
|                  |                               | Discharging| 61.71                         | 58.04              | 175.2             |
|                  | 3.0                           | Charging| 55.54                         | 62.34              | 175.0             |
|                  |                               | Discharging| 61.66                         | 57.92              | 168.7             |
| P + ZnO         | 1.0                           | Charging| 55.75                         | 60.69              | 187.4             |
|                  |                               | Discharging| 61.58                         | 58.38              | 182.2             |
|                  | 2.0                           | Charging| 55.01                         | 61.31              | 184.7             |
|                  |                               | Discharging| 61.73                         | 58.46              | 178.5             |
|                  | 3.0                           | Charging| 55.02                         | 60.57              | 171.9             |
|                  |                               | Discharging| 61.69                         | 58.65              | 167.5             |

Figure 10 Melting onset temperature ratio of the NEPCMs.

Figure 11 Melting peak temperature ratio of the NEPCMs.
layer subjected to temperature changes has a relatively large expansion or contraction ratio, which will harm the combination of additives with paraffin and thereby reduce the thermal storage and heat conduction performance of the NEPCMs. Therefore, the suspension performances of additives, as well as the combination of additives and paraffin, are critical factors determining the heat conduction and thermal storage performance of NEPCMs.

In this study, the thermal conductivity of the additives was higher than that of paraffin. According to the calculations of thermal conductivity and temperature difference experiment, additives with a higher thermal conductivity than that of paraffin can enhance the thermal conductivity of the paraffin [43]. However, an additive in paraffin reduces the phase-change heat of the paraffin due to the fact that the additives do not cause phase change in the experimental temperature range. Such phenomena will reduce the unit volume of heat storage capacity and reduce the overall benefits of thermal storage. However, if the additives can reduce the onset temperature of the melting process or increase the onset temperature of the solidification process of NEPCMs, they will be able to enhance the usage range of phase-change heat of NEPCMs, thereby increasing the rate of charging and discharging more effectively in...
response to changes in the heat load due to phase-change heat having a large heat capacity. Therefore, in selecting the optimal additives, we must also consider the heat conduction performance and the range of phase-change temperature and phase-change heat. The experimental results show that adding TiO₂ to paraffin can increase the range of phase-change temperatures and heat conduction performance, thereby increasing the temperature range of phase-change heat and the response rate of the thermal load that can be applied to heat storage. Furthermore, the NEPCMs with TiO₂ have a minimum decreased ratio of phase-change heat of only 0.46% for maintaining an optimum heat storage capacity. Therefore, adding TiO₂ to paraffin to enhance heat storage performance has notable potential for future applications.

Conclusions
This study used a direct-synthesis method to prepare NEPCMs by adding varying concentrations of Al₂O₃, TiO₂, SiO₂, and ZnO nano-additives to paraffin. Through both the heat conduction and DSC experiments, we investigated the effects of varying the concentrations of the nano-additives on heat conduction performance and heat storage performance. Experimental results demonstrate that TiO₂ is more effective than the other nano-additives in modifying the heat conduction and thermal storage performance of paraffin. Adding TiO₂ can increase the heat conduction performance, reduce the melting onset temperature, and increase the solidification onset temperature of paraffin. This allows the application of phase-change heat to respond to rapid heat load changes and a wider temperature range, and the highest decreased ratio of phase-change heat is only 0.46%, compared to that of paraffin. Therefore, the use of TiO₂ for enhancing the heat conduction and thermal storage performance of paraffin is a method that has great potential for future applications.

Competing interests
The authors declare that they have no competing interests.

Authors’ contributions
TPT designed the experiment and fabricated the samples. TPT and CCY carried out the measurements, analyzed the measurements, and wrote the paper. All authors read and approved the final manuscript.

Acknowledgements
The authors would like to thank the National Science Council of the Republic of China, Taiwan, for their financial support to this research under contract nos. NSC 98-2221-E-003-018- and NSC 99-2221-E-003-008-.

Received: 6 September 2012 Accepted: 27 October 2012 Published: 6 November 2012

References
1. Zalba B, Marin JM, Cabeza LF, Mehling H: Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Therm Eng 2003, 23:251.
2. Farid MM, Khudhair AM, Razack SA, Al-Hajal S: A review on phase change energy storage: materials and applications. Energy Convers Manage 2004, 45:1597.
3. Najari A, Hasan A: Modeling of greenhouse with PCM energy storage. Energy Convers Manage 2008, 49:3338.
4. Hawes DW, Feldman D, Banu D: Latent heat storage in building materials. Energy Build 1993, 20:77.
5. Velraj R, Seeniraj R, Hafrner B, Faber C, Schwarzer K: Heat-transfer enhancement in a latent-heat storage system. Sol Energy 1999, 65:171.
6. Parapathy A, Velraj R, Seeniraj R: Phase change material-based building architecture for thermal management in residential and commercial establishments. Renew Sustain Energy Rev 2008, 12:39.
7. Kizawa A, Kamano H, Kawai A, Jozuka T, Senda T, Manouka N, Akiyama T: Thermal and flow behaviors in heat transportation container using phase change material. Energy Convers Manage 2008, 49:598.
8. Baetens R, Petter Jelle B, Gustavsen A: Phase change materials for building applications: a state-of-the-art review. Energy Build 2010, 42:1361.
9. Jiang F, Wang X, Zhang Y: A new method to estimate optimal phase change material characteristics in a passive solar room. Energy Convers Manage 2011, 52:2437.
10. Kuznik F, David D, Johannes K, Roux J: A review on phase change materials integrated in building walls. Renew Sustain Energy Rev 2011, 15:379.
11. Fan LW, Khosdeladi JM: Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renew Sustain Energy Rev 2011, 15:24.
12. Marin JM, Zalba B, Cabeza LF, Mehling H: Improvement of a thermal energy storage using plates with paraffin–graphite composite. Int J Heat Mass Transf 2005, 48:2561.
13. Zhang YP, Ding JH, Wang X, Yang R, Liu KP: Influence of additives on thermal conductivity of shape-stabilized phase change material. Sol Energy Mater Sol Cells 2006, 90:1692.
14. Wang JF, Xie HQ, Xin Z, Li Y, Chen LF: Enhancing thermal conductivity of palmitic acid based phase change materials with carbon nanotubes as fillers. Sol Energy 2010, 84:339.
15. Cai Y, Wei Q, Huang F, Gao W: Preparation and properties studies of halogen-free flame retardant form-stable phase change materials based on paraffin/high density polyethylene composites. Appl Energy 2008, 85:765.
16. Shaltikian V, Ziskand G, Letan R: Numerical investigation of a PCM-based heat sink with internal fins. Int J Heat Mass Transf 2005, 48:3689.
17. Gharabaghi M, Sezai I: Enhancement of heat transfer in latent heat storage modules with internal fins. Numer Heat Transf A 2008, 53:749–765.
18. Aygunem F, Eames P, Smyth M: A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins. Sol Energy 2009, 83:1509.
19. Sari A, Karapeki A, Alkan C: Preparation, characterization and thermal properties of lauric acid/expanded perlite as novel form-stable composite phase change material. Chem Eng J 2009, 155:699.
20. Karapeki A, Sari A: Capric–myristic acid/vermiculite composite as form-stable phase change material for thermal energy storage. Sol Energy 2009, 83:323.
21. Kim S, Drzal LT: High latent heat storage and high thermal conductive phase change materials using exfoliated graphite nanoplatelets. Sol Energy Mater Sol Cells 2009, 93:136.
22. Li JL, Xue P, Ding WY, Han JM, Sun GL: Micro-encapsulated paraffin/high-density polyethylene/wood flour composite as form-stable phase change material for thermal energy storage. Sol Energy Mater Sol Cells 2009, 93:1761.
23. Zhao CY, Lu W, Tian Y: Heat transfer enhancement for thermal energy storage using metal foams embedded within phase change materials (PCMs). Sol Energy 2010, 84:402.
24. Zhou D, Zhao CY: Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials. Appl Therm Eng 2013, 31:970.
25. Li M, Wu Z, Kao H, Tan J: Experimental investigation of preparation and thermal performances of paraffin/bentonite composite phase change material. Energy Convers Manage 2011, 52:3275.
26. Li HQ, Qu ZG, He YL, Tao WQ: Experimental and numerical studies on melting phase change heat transfer in open-cell metallic foams filled with paraffin. Appl Therm Eng 2012, 37:1.
27. Oya T, Nomura T, Okinaka N, Akiyama T: Thermal conductivity of shape-stabilized phase change material for thermal energy storage using plates with paraffin. Appl Therm Eng 2012, 37:3.
28. Hu J, Yu H, Chen YM, Zhu MF: Study on phase-change characteristics of PET–PEG copolymers. J Macromol Sci B 2006, 45:515.
29. Karaipekli A, San A, Kaygusuz K: Thermal conductivity improvement of stearic acid using expanded graphite and carbon fiber for energy storage applications. Renew Energy 2007, 32:2201.
30. Wang MR, Kang CJ, Pan N: Thermal conductivity enhancement of carbon fiber composites. Appl Therm Eng 2009, 29:418.
31. Chen C, Wang L, Huang Y: Electrospun phase change fibers based on polyethylene glycol/cellulose acetate blends. Appl Energy 2011, 88:3133.
32. Hawlader MNA, Uddin MS, Khin MM: Microencapsulated PCM thermal-energy storage system. Appl Energy 2003, 74:195.
33. Sari A, Alkan C, Karaipekli A, Uzun O: Microencapsulated n-octacosane as phase change material for thermal energy storage. Sol Energy 2009, 83:1757.
34. Chen ZH, Yu F, Zeng XR, Zhang ZG: Preparation, characterization and thermal properties of nanocapsules containing phase change material n-dodecanol by miniemulsion polymerization with polymerizable emulsifier. Appl Energy 2012, 91:7.
35. Shaikh S, Lafki K, Hallinan K: Carbon nano additives to enhance latent energy storage of phase change materials. J Appl Phys 2008, 103:094302.
36. Wang JF, Xie HQ, Xin Z: Thermal properties of paraffin based composites containing multi-walled carbon nanotubes. Thermochim Acta 2009, 488:39.
37. Cui Y, Liu C, Hu S, Yu X: The experimental exploration of carbon nanofiber and carbon nanotube additives on thermal behavior of phase change materials. Sol Energy Mater Sol Cells 2011, 95:1208.
38. Elgafy A, Lafki K: Effect of carbon nanofiber additives on thermal behavior of phase change materials. Carbon 2005, 43:3067.
39. Ho CJ, Gao Y: Preparation and thermophysical properties of nanoparticle-in paraffin emulsion as phase change material. Int Commun Heat Mass Transf 2009, 36:467.
40. Teng TP, Lin BG, Yeh YY: Characterization of heat storage by nanocomposite-enhanced phase change materials. Adv Mater Res 2011, 287:148.
41. Arasu AV, Mudumdar AS: Numerical study on melting of paraffin wax with Al2O3 in a square enclosure. Int Commun Heat Mass Transf 2012, 39:3.
42. Zeng JL, Sun LX, Xu F, Tan ZC, Zhang ZH, Zhang J, Zhang T: Study of a PCM based energy storage system containing Ag nanoparticles. J Therm Anal Calorim 2007, 87:369.
43. Maxwell JC: A Treatise on Electricity and Magnetism. Volume 1. 3rd edition. Oxford: Clarendon; 1904.