



Research paper

Development of sunlight-driven eutectic phase change material nanocomposite for applications in solar water heating[☆]

S. Shankara Narayanan*, Abhishek Kardam, Vivek Kumar, Nitin Bhardwaj, Devinder Madhwal, Prashant Shukla, Amit Kumar, Abhishek Verma, V.K. Jain

Amity Institute for Advanced Research and Studies (Materials & Devices) & Amity Institute of Renewable and Alternate Energy, Amity University, Uttar Pradesh, Noida 201313, India

ARTICLE INFO

Article history:

Received 16 November 2016
 Revised 13 December 2016
 Accepted 17 December 2016
 Available online 6 January 2017

Keywords:

Phase change material (PCM)
 Eutectic gel PCM Nanocomposite
 Ultrafast charging
 Solar water heating
 Solar rechargeable glove

ABSTRACT

Organic phase change materials (PCMs) have been utilized as latent heat energy storage medium for effective thermal management. In this work, a PCM nanocomposite, consisting of a mixture of two organic PCMs (referred to as eutectic gel PCM) and minimal amount (0.5 wt%) of nanographite (NG) as a supporting material, was prepared. Differential scanning calorimeter was used to determine the melting temperature and latent heat of pristine PCM, paraffin (61.5 °C and 161.5 J/g), eutectic gel PCM (54 °C and 158 J/g) and eutectic gel PCM nanocomposite (53.5 °C and 155 J/g). The prepared PCM nanocomposites exhibited enhanced thermal conductivity and ultrafast thermal charging characteristics. The nanocomposites were employed for two different applications: (i) providing hot water using an indigenously fabricated solar water heating (SWH) system and (ii) solar rechargeable glove that can be rapidly warmed and used. Experimental results on SWH system show that the use of PCM nanocomposites helps to increase the charging rate of PCM while reducing the discharging rate of heat by PCM to water, thus enhancing the maximum utilization of solar energy and hence improving the efficiency of the SWH system. The experimental results on solar rechargeable glove revealed that the glove has the ability to retain the temperature up to 3 hours.

© 2016 Tomsk Polytechnic University. Published by Elsevier B.V.
 This is an open access article under the CC BY-NC-ND license.
[\(http://creativecommons.org/licenses/by-nc-nd/4.0/\)](http://creativecommons.org/licenses/by-nc-nd/4.0/)

1. Introduction

Thermal energy storage (TES) using phase change materials (PCMs) have drawn a lot of attention in recent years due to their ability to store and release large amounts of heat energy in response to a small temperature change and high energy storage capacity [1–3]. PCMs have been widely used in different applications, such as underfloor heating system [4], refrigeration system [5], electronics cooling [6], waste heat recovery [7], textiles [8], preservation of food and milk [9], dermal therapies [10] and solar water heater [11]. PCMs have been broadly classified into two types: organic and inorganic. Among these, organic PCMs have been extensively studied due to their high latent heat storage ca-

capacity, small volume change, little or no supercooling, high chemical and thermal stability [2]. Organic PCMs are further classified into two categories: paraffins and non-paraffins. Paraffins, a mixture of straight chain n-alkanes, are one of the most commonly used organic PCMs for TES and exhibit desirable properties like large latent heat, low cost, stability, non-toxicity, and chemical inertness [1]. Non-paraffin PCMs are classified into fatty acids and other non-paraffin organic. Fatty acids, known by the chemical formula $\text{CH}_3(\text{CH}_2)_{2n}\text{COOH}$, exhibit desirable thermodynamic and kinetic characteristics, such as congruent melting, large latent heat of transition, and reproducible melting and freezing behavior, with little or no supercooling [3].

An organic eutectic PCM is a combination of two or more organic PCMs. It acts as a single component and freezes to an intimate mixture of crystals and melts simultaneously without separation. A considerable number of organic eutectics may be tailored to almost any desired melting point for TES systems. For example, a mixture of 45% by weight of a paraffin wax (melting point ~53 °C) obtained from the refining of crude petroleum and 55% by weight of commercial grade stearic acid (melting point

[☆] Peer review under responsibility of Tomsk Polytechnic University.

* Corresponding author. Amity Institute for Advanced Research and Studies (Materials & Devices) & Amity Institute of Renewable and Alternate Energy, Amity University, Uttar Pradesh, Noida 201313, India. Tel.: +91 120 4392189; fax: +91 120 4392289.

E-mail address: shankar334@gmail.com (S.S. Narayanan).

~53 °C) leads to a eutectic PCM having a melting point of 42 °C, which has been used for TES [12]. As the use of organic eutectic PCMs is very new to TES application, only limited data are available on their thermal properties. For instance, the latent heat storage characteristics of binary eutectic mixtures of lauric acid–stearic acid, myristic acid–palmitic acid and palmitic acid–stearic acid were studied using DSC for several melting/freezing cycles and used for passive solar TES applications [13]. In another study, the thermal properties of a caprylic acid/1-dodecanol binary eutectic mixture were investigated and used as cold storage material for air conditioning [14]. However, a major drawback of using organic eutectic PCM is its poor heat transfer performance due to the low thermal conductivity of organic PCMs involved. In order to enhance the heat transfer ability of organic PCM for TES application, various techniques have been investigated such as usage of mechanically supporting and thermally conductive foams, preparation of phase change composites by mixing the PCMs with thermally conductive carbonaceous materials of various shapes such as graphite nanoplatelets, expanded graphite, carbon nanotubes and nanofibers, and dispersion of PCMs into highly thermally conductive porous structures [15–18]. Similarly, to enhance the ability of organic eutectics for TES applications, the addition of thermally conductive carbon nanomaterials to prepare nano-organic eutectic PCM composites has been proposed in the literature. For instance, shape-stabilized PCMs based on fatty acid eutectics/expanded graphite composites were prepared and used for TES [19]. In another study, capric–myristic–palmitic acid/exfoliated graphite composite PCM [20] and capric–lauric–palmitic acid eutectic mixtures/expanded graphite PCM composite [21] were prepared and their thermal properties were investigated.

One of the potential applications of PCMs is in solar water heating (SWH) system, since PCMs offer high energy storage density. A suitable PCM with its melting point in the desired temperature range is one of the most important parameters in the design of a SWH system. Few literatures are available on the use of PCM for SWH applications. For example, Sharma and Chen reviewed energy storage using PCMs for SWH systems and attempted to summarize the investigation of these systems [22]. Islam et al. presented an overview of various types of solar assisted water heating systems and their market potential [23]. Otanicar and Golden made a comparative environmental and economic analysis of conventional and nanofluid solar hot water technologies for the Phoenix, Arizona region [24]. Another potential and interesting application of the PCMs is in clothing [25]. For example, the thermal insulation capabilities of cold protective clothing materials may be significantly improved by the incorporation of PCM microcapsules, which differ significantly from the insulation properties of any other material [26]. PCMs have been used to provide thermal comfort in a wide variety of garments. Extreme heat/cold related problems are being faced by Indian forces working in very harsh environment in hot deserts at western border and cold deserts at high altitudes like thermal discomfort and failure of mission-critical equipment. Use of PCMs can provide practical solutions to many of these problems. For example, a PCM-based cool vest, having removable PCMs packs in multiple pockets, have been developed by Defence Laboratory Jodhpur (DLJ), India, to provide comfortable microenvironment for soldiers on field duties (below 30 °C) for 2–3 hours [27]. PCMs have also been used in space suits and gloves to protect astronauts from extreme temperature fluctuations in space [25].

The present research article describes an experimental investigation of nano-organic eutectic PCM composite consisting of a mixture of two organic PCMs (paraffin wax and oleic acid) and minimal amount (0.5 wt%) of a nanomaterial in the form of nanographite (NG). This novel composite is referred to as nano eutectic gel phase change material (NEGPCM). The novelty of the current research work involves the development of stable sunlight

driven NEGPCM composites for solar thermal energy storage applications in solar water heater and gloves. In addition an indirect passive solar water heating system is designed and fabricated which is capable of providing continuous hot water under direct solar illumination using NEGPCM composites. Simultaneously, the NEGPCM composite is able to retain its latent heat for prolonged period, which can be used for hot water generation during night-time or in the absence of solar radiation. In another application, NEGPCM composites were used for preparing a glove, which can be either worn or can be used as a pad for providing thermal comfort in extreme cold environment.

2. Experimental section

2.1. Materials

The organic PCM, paraffin wax, with melting temperature range of 60–62 °C was adopted as the pristine PCM, while commercially available nanographite (NG) powder, with an average particle size of 150 nm, was procured from Reinste, Germany. Oleic acid (fatty acid) and bulk graphite were procured from Merck, India.

2.2. Preparation of nano eutectic gel phase change material (NEGPCM) composites

The NEGPCM was prepared using the melt mixing technique [28] involving two organic PCMs: (a) paraffin wax (m.p. 60–62 °C), (b) oleic acid (m.p. 13–14 °C), and dispersed nanomaterials in the form of nanographite. In a typical procedure, 50 g of solid paraffin wax (PW) was melted with the help of a hot plate (IKA RCT basic). Using a magnetic stirrer, the molten PW was mixed thoroughly with 56 mL of oleic acid (density of oleic acid = 0.89 g/mL at 25 °C) to formulate an organic eutectic PCM. The resultant organic eutectic PCM was in gel form at room temperature and referred to as eutectic PCM gel. Nanomaterial in the form of NG (0.5 wt%) was then added to eutectic PCM gel and vigorously stirred for 15 min to form nano eutectic gel phase change material (NEGPCM) composites. Finally, the as prepared composites were ultrasonicated (Telesonic, Ultrasonics) for approximately 2 min to obtain a homogeneous dispersion of NG in the NEGPCM composite.

2.3. Characterization and measurements

The morphology and microstructure of materials were determined with the help of scanning electron microscope (SEM) on a Zeiss (EVO-18). The phase transition temperatures and latent heats of pristine PCM, eutectic gel PCM and NEGPCM composites were obtained using differential scanning calorimeter (DSC, TA Instruments Q100) at a heating rate of 10 °C/min. A thermal imager with digital camera (Testo 875-i1) with a thermal sensitivity < 50 mK was used to capture the PCM temperature distribution within the thermal energy storage tank. Thermal conductivity measurements were conducted with a Linseis Transient Hot Bridge-Thermal Conductivity Meter (THB6N43), an instrument based on the hot disk technique. Thermal conductivity of the material was measured by placing the temperature sensor between two samples having parallel plane surfaces to ensure a good contact between the sensor and the material. In order to investigate the transient heat transfer during melting and solidification of NEGPCM composites, a conventional heating experimental setup featuring a heated-from-below configuration was designed. The set-up consisted of a hot plate having a set temperature range of 30–400 °C and an attached temperature sensor. The details of the setup can be referred from our previous publication [29].

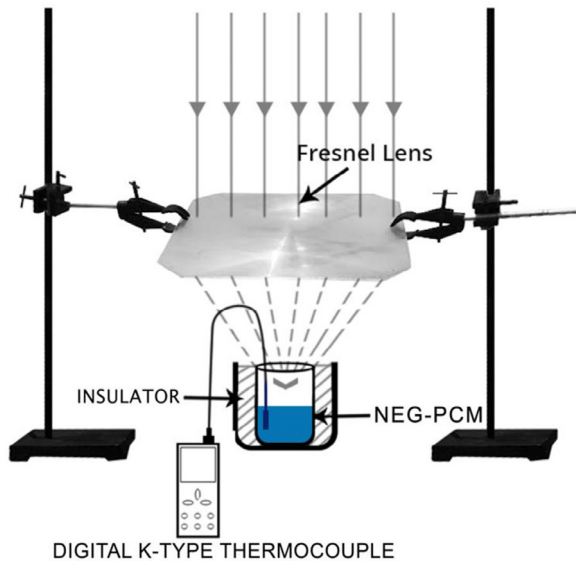


Fig. 1. Schematic diagram of the solar illumination experimental setup showing the ultrafast thermal charging of nano eutectic gel PCM (NEGPCM) upon illumination with solar radiation focused by a 30 cm × 30 cm Fresnel lens.

2.4. Solar illumination experimental setup

The photon-to-thermal energy conversion of pristine PCM, eutectic gel PCM and NEGPCM composites was investigated under the solar radiation (average intensity of 750 W/m²) using the experimental setup shown in Fig. 1. The intensity of solar radiation was measured using a pyranometer (Hukseflux USA, model SR11 first class pyranometer). The solar illumination experiments were carried out by focusing sunlight (using a fresnel lens with area of 30 cm × 30 cm) into a 20 mL beaker containing NEGPCM composites and the temperature of composites was monitored using a k-type thermocouple (TC). In the present work, the NEGPCM composite has been used for two important applications: (i) solar water heating system and (ii) solar rechargeable glove with ultrafast thermal charging characteristic. In the following section, the two applications are discussed in detail.

2.5. Solar water heating system

One of the potential applications of solar thermal energy storage is in solar water heating (SWH). In the present work, a NEGPCM-based solar water heating system has been designed and fabricated. Fig. 2 presents the proposed solar water heating system. It is an indirect passive SWH system, which consists of three major components: (i) a solar collector unit (a 60 cm × 45 cm area Fresnel lens), (ii) a thermal energy storage (TES) unit filled with NEGPCM and (iii) a well-insulated water storage tank. The inside of the TES unit consists of copper tank surrounded by densely packed 14 turns of copper coils having an inner and outer diameter of 3 and 6 mm, respectively. A multiple thermal insulation is provided to the unit consisting of glass fiber, glass wool (50 mm) and polymer material, which prevent leakage of thermal energy to external surroundings. Similar thermal insulation has been provided for the lid of the TES unit. A cross-sectional view of the TES tank, revealing all the details, is shown in Fig. 3. During the charging process, the copper tank containing 450 mL of NEGPCM is illuminated with solar radiation focused by a 60 cm × 45 cm area Fresnel lens. Simultaneously, cold water is circulated through the TES tank continuously. The initial temperature of water was 30 ± 0.5 °C. As the NEGPCM composite was illuminated, the cold water flows from the inlet to the copper tank, absorbing the heat from the melted

NEGPCM in the process. The hot water, thus generated, is then stored in a separate thermally insulated storage tank. As shown in Fig. 2, five thermocouples (TCs) have been used in SWH heating system, which is used to record the temperature of NEGPCM and water at different locations. Three thermocouples (TC1, TC2 and TC3) were placed at different heights inside the TES unit to monitor the temperature of the NEGPCM composites. The remaining two thermocouples, TC5 and TC4, were placed near the cold-water inlet and hot water outlet, respectively, to monitor the temperature of water. We also studied the discharging characteristics by monitoring the temperature of water at different intervals of time, upon closing the lid of TES tank and insulating it from the surroundings.

2.6. Nano eutectic gel phase change material (NEGPCM)-based solar rechargeable glove

In another application, NEGPCM composites were used to develop a hand glove (Fig. 4), having ultrafast charging characteristics under solar illumination. The NEGPCM-based hand glove comprises an outer protective layer, a middle NEGPCM envelope, and an inner conformable layer, preferably made of flexible material, which can sustain the required temperature. Fig. 5 shows the NEGPCM composite based glove being illuminated with solar radiation and focused by a 30 cm × 30 cm Fresnel lens on a small glass window provided at the center of the glove. The small glass window prevents the overheating of the hand glove. Upon solar illumination, the NEGPCM inside the glove absorbs the solar radiation and rapidly converts it into thermal energy due to the presence of highly thermal conductive nanofiller (nanographite). Thus, NEGPCM composite based glove demonstrated an ultrafast thermal charging which resulted in shortening of the melting time of NEGPCM composites to 3 minutes. As the glove is provided with a suitable thermal insulation in the form of cotton wool, there is no leakage of thermal energy to the surroundings and the glove was able to store and maintain thermal energy for a longer duration. Our experimental observations showed the heat retention in gloves occurred up to ~3 hours. The NEGPCM based solar rechargeable hand glove is an easy to use glove that can be worn over a person's hand and/or wrist, or can be given the shape of a heating pad to be placed on any part of the human body for hot fomentation. The effect of PCMs on hand skin temperature within gloves of soccer goalkeepers has been studied by Purvis and Cable [30]. Their results suggested that the particular specification of PCM used by them promoted heat gain rather than heat loss and are therefore inappropriate to enhance thermal comfort in their setting. We believe that our prepared novel sunlight-driven NEGPCM composites could have important potential application in renewable and clean energy sources and further research is being carried out to diversify applications of PCMs to address problems of extreme climates being faced by Armed Forces like hot jackets for high altitude areas and high capacity heat sinks for critical instruments.

3. Results and discussion

3.1. Morphological characterization of NEGPCM composites

SEM images were taken to observe the dispersion of NG in eutectic gel composite and morphology of the prepared NEGPCM composites. The SEM image of the pristine NG is shown in Fig. 6a, which reveals a size distribution of 100–200 nm. The SEM images of pristine paraffin wax and NEGPCM composites are shown in Fig. 6b and c, respectively, which clearly indicates that NGs are well dispersed in the eutectic gel PCM composite. The uniform dispersion of NG throughout the matrix of eutectic gel occurs because of the compatible interface between the NGs and eutectic gel PCM,

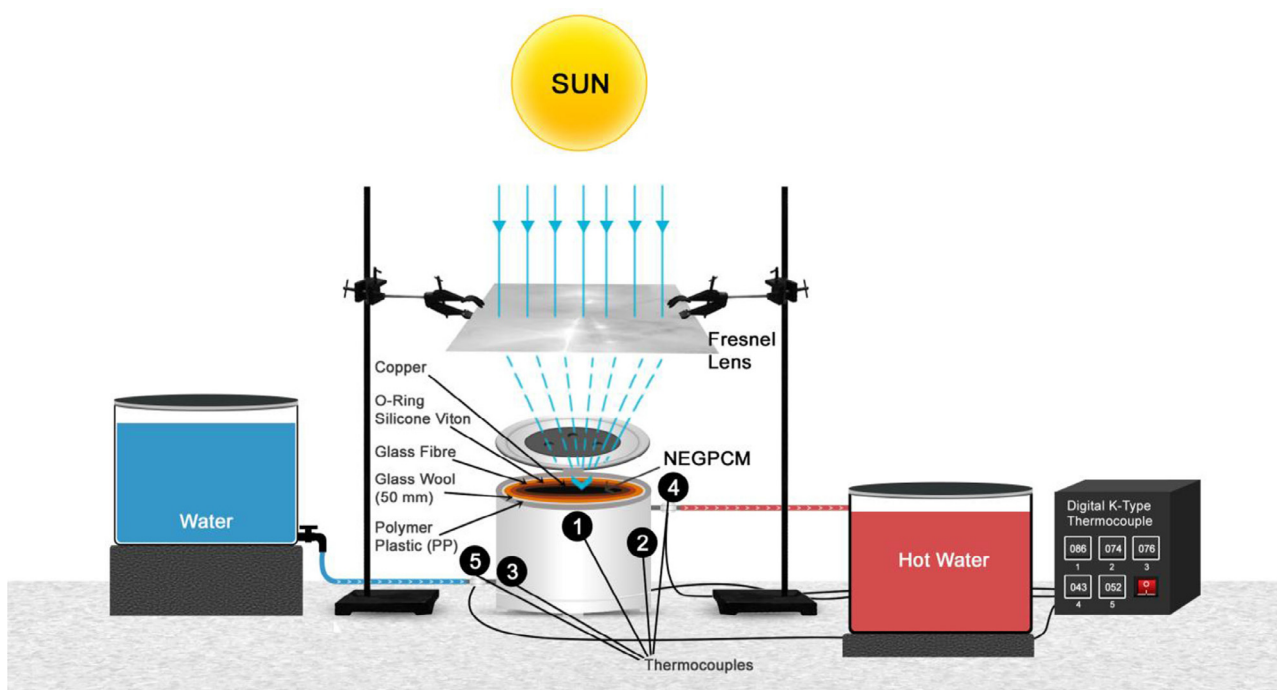


Fig. 2. Schematic diagram of solar water heating system showing a water storage tank, thermal energy storage tank containing nano eutectic gel phase change material composite (NEGPCM), five thermocouples (numbered from 1 to 5) for sensing the temperature of NEGPCM composite and the hot water, and an insulated hot water storage tank. The copper tank containing NEGPCM composite was irradiated by a 60 cm × 45 cm Fresnel lens.

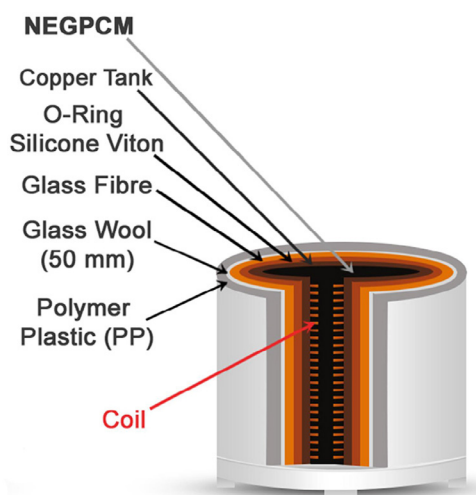


Fig. 3. Cross-sectional view of thermal energy storage (TES) tank of solar water heating system.

enabling a three-dimensional network of superfast heat conduction. It is to be noted that there is no chemical reactivity between the nanoparticles and the PCM, they are merely physically mixed to form a nano-PCM composite.

3.2. Thermal properties of NEGPCM composites

Thermal energy storage properties of pristine paraffin, eutectic gel PCM and NEGPCM composites were examined with DSC. Fig. 7 shows the heating curves obtained with DSC measurements of pure paraffin, eutectic gel PCM and NEGPCM. The DSC curve of pure paraffin (Fig. 7a) revealed a sharp peak representing a single melting temperature (T_m) of the paraffin, which occurs at 61.5 °C. The latent heat of pure paraffin wax was calculated by



Fig. 4. Photograph of nano eutectic gel phase change material (NEGPCM) composite based hand glove, with ultrafast charging characteristics, developed for use in higher altitudes where less sunshine occurs/where is no external power available.

measuring the area under the peak and found to be 161.5 J/g. The latent heat of oleic acid, which is a colorless liquid at ambient temperature, is 140 J/g, according to NIST Standard reference database. Fig. 7b presents the DSC plot of the paraffin/oleic acid (eutectic gel PCM). The melting temperature of eutectic gel PCM was found to be 54 °C and the latent heat of eutectic gel PCM was found to be 158 J/g. It is to be noted that the measured latent heat of eutectic gel PCM is found to be in close agreement with the value it should have (151 J/g) according to the proportion of the pure components added (~1:1 ratio) to make eutectic gel PCM. In addition, the DSC analysis of NEGPCM composites (Fig. 7c) was also carried out to investigate the effect of NG on the phase change behavior of PCM in the composites. The melting temperature and latent heat of NEGPCM composites were measured to be 53.5 °C and 155 J/g, respectively. It is clear that the latent heat of fusion of NEGPCM

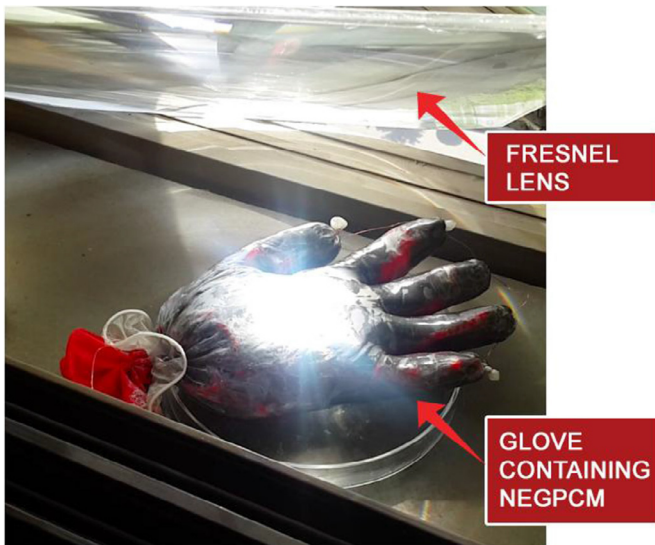


Fig. 5. Photograph of nano eutectic gel phase change material (NEGPCM) composite based glove illuminated with solar radiation.

Table 1

Thermal conductivity values of pristine paraffin, bulk graphite–paraffin composite at 0.5 wt% of bulk graphite and nanographite (NG)–paraffin composite at 0.5 wt% of NG.

PCM	Thermal conductivity coefficient (W/(mK))
Pristine paraffin	0.182
Bulk graphite–paraffin composite (at 0.5 wt% of bulk graphite)	0.286
NG–Paraffin composite (at 0.5 wt% of NG)	0.662

composites decreased in the presence of NG. However, the slight decrease of the latent heat of the NEPCM composites cannot be attributed to the lower fraction of PCMs alone. Another factor leading to the loss of the latent heat is due to the introduction of NG layers into paraffin, which affected the phase change process [31]. The observed decrease in the latent heat of the NEPCM composites in the present study is in agreement with the results obtained in the literature [32].

It is well known that PCMs store and release thermal energy while melting and solidifying. The rate of storing and releasing thermal energy is highly related to PCM thermal conductivities. It is important to mention here that on account of difficulty in measuring the thermal conductivities of the prepared eutectic gel PCM composite and NEPCM composite, the thermal conductivities of paraffin and NG–paraffin composite were measured in order to assess the effect of NG in enhancing the thermal conductivity of paraffin. The results are summarized in Table 1. The measured thermal conductivity for the pristine paraffin, $k = 0.182 \text{ W/(mK)}$, at room temperature is in agreement with the value reported in the literature [31]. On addition of 0.5 wt% of NG to paraffin, the thermal conductivity of the NG–paraffin composite increased to 0.662 W/(mK) . In addition, bulk graphite–paraffin composite was also measured to benchmark the improvement of the thermal properties of the NG–paraffin composites. The thermal conductivity of the bulk graphite–paraffin composite (at 0.5 wt% of bulk graphite) was measured and found to be 0.286 W/(mK) . This represents an over 264% thermal conductivity enhancement of NG–paraffin composite as compared to the pristine paraffin and 131% enhancement as compared to bulk graphite–paraffin composite. The above studies clearly indicate that the thermal conductivity of

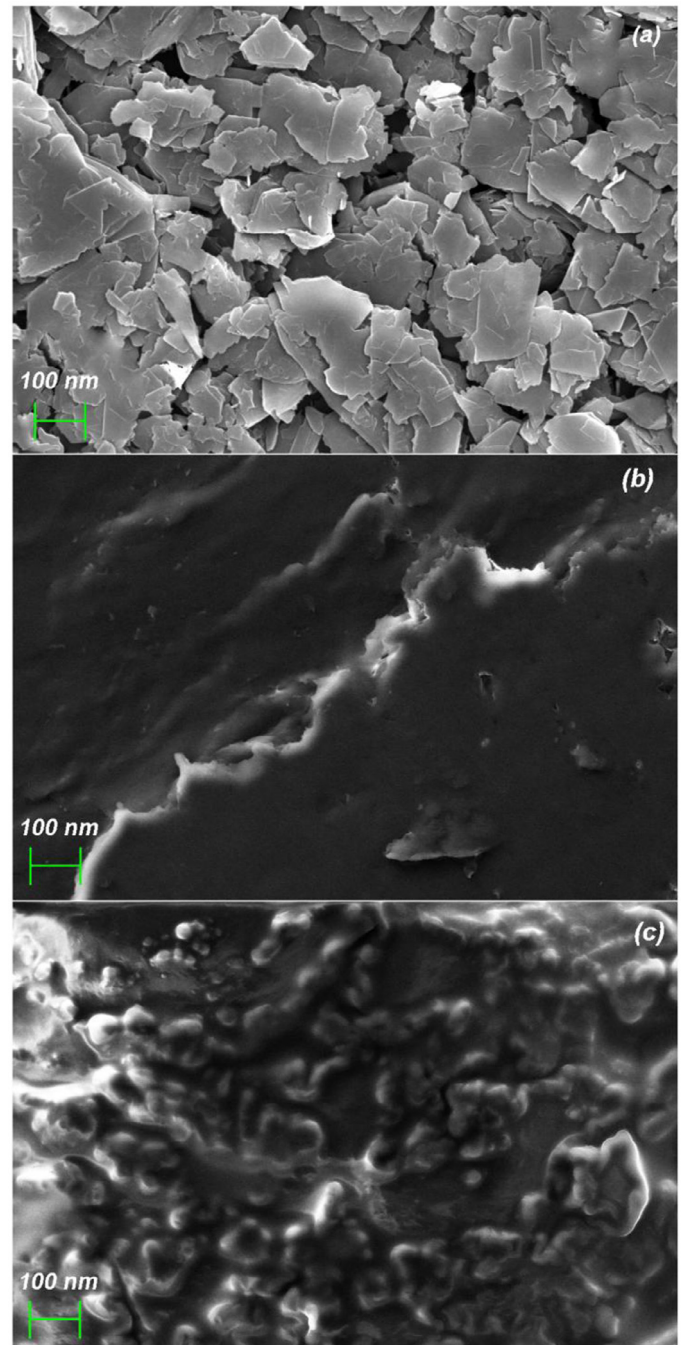


Fig. 6. SEM images showing morphology of (a) nanographite (NG), (b) pristine paraffin and (c) nano eutectic gel phase change material (NEGPCM) composite at a nanographite loading of 0.5 wt%.

paraffin is considerably enhanced by the presence of NG. This enhancement can be attributed to the thermal conductive network of NG fillers providing a pathway of lower resistance for phonon transport [33].

3.3. Solar illumination

The solar illumination experiments were conducted to compare the rate of charging (melting) of pristine paraffin, eutectic gel and NEPCM composites upon solar illumination. The experimental setup for the solar illumination experiment is shown in Fig. 1 and the results are summarized in Table 2. The experimen-

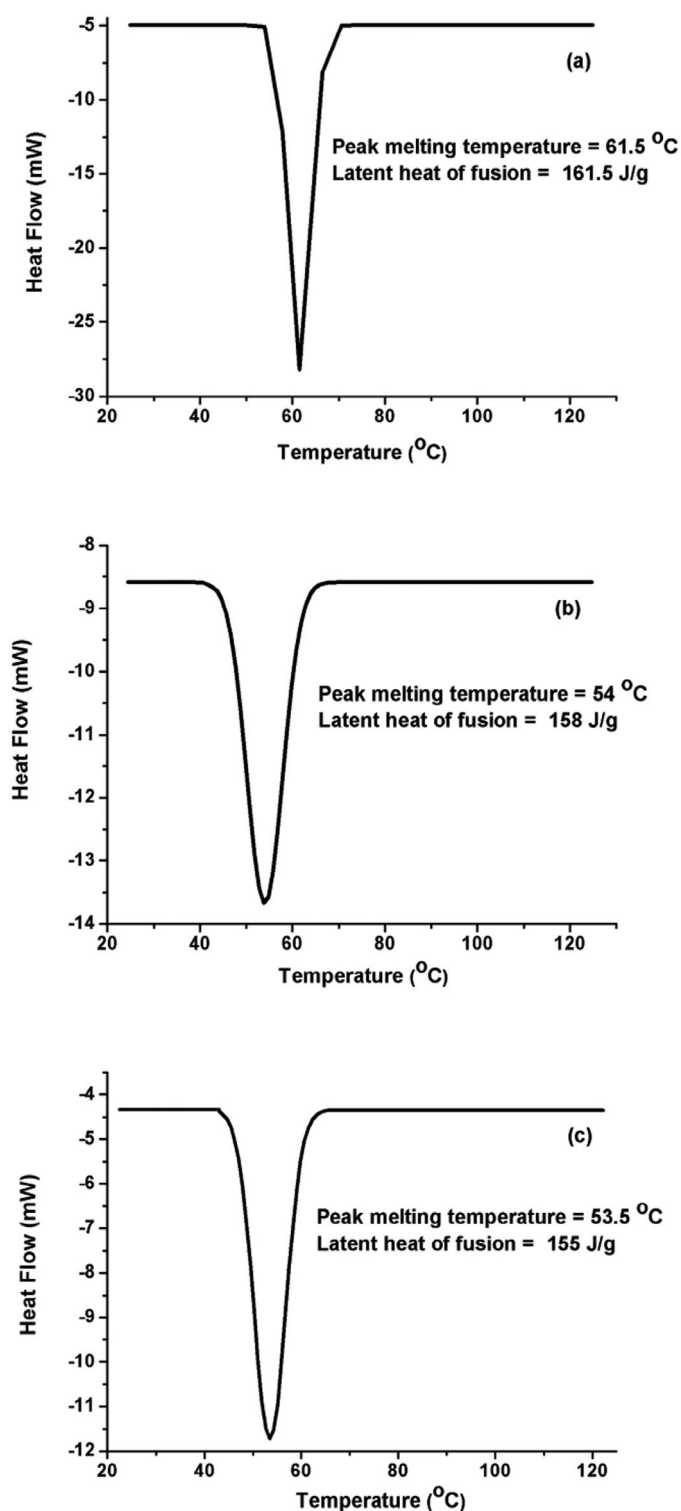


Fig. 7. Differential scanning calorimetry (DSC) plots of (a) pristine paraffin, (b) Eutectic gel PCM and (c) nano eutectic gel phase change material (NEGPCM) composite.

tal observations clearly indicate drastic reduction in the melting time of NEGPCM composites as compared to pristine paraffin and eutectic gel PCM. It was observed that the time taken to completely melt pristine paraffin and eutectic gel was 1 hour 30 minutes and 45 minutes, respectively (Table 2). On the other hand, the melting time of NEGPCM composites (at 0.5 wt% of NG) was drastically reduced to 3 minutes. This represents an overall enhancement

Table 2

Melting time of different PCMs upon illumination with solar radiation focused by a 30 cm × 30 cm Fresnel lens.

PCM	Melting time of the PCM
Paraffin wax (PW)	1 hour 30 minutes
Eutectic gel (PW + oleic acid)	45 minutes
Eutectic gel + 0.5 wt% bulk graphite	20 minutes
Eutectic gel + 0.5 wt% nanographite (NEGPCM composite)	3 minutes

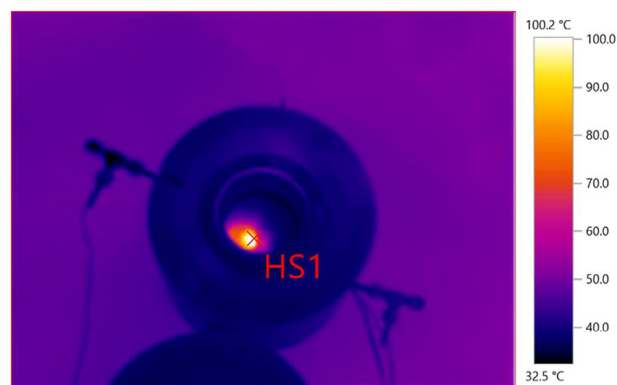


Fig. 8. IR image of NEGPCM composite inside the TES tank under solar illumination.

of 93% in the melting rate of the NEGPCM composite compared to that of eutectic gel PCM. Therefore, compared with eutectic gel, NEGPCM composites have a high thermal conductivity, which improves the energy utilization efficiency during heat charging process. To confirm the efficacy of NG in enhancing the thermal conductivity of eutectic gel PCM, another experiment was performed in which NG was replaced with bulk graphite and the melting time of resulting bulk graphite–eutectic gel PCM composite was monitored. The melting time of such a composite system was found to be 20 minutes. This represents an overall enhancement of 55% in the melting rate of the bulk graphite–eutectic gel PCM composite compared to that of eutectic gel PCM. The comparison of the melting rates of the NEGPCM composite (enhancement of 93%) and the bulk graphite–eutectic gel PCM (enhancement of 55%) composite clearly indicates that nanographite in NEGPCM acts an effective photon captor and molecular heater by converting light into heat energy.

The temperature distribution of the NEGPCM composite was recorded by the thermal imaging IR camera as shown in Fig. 8. Under solar illumination, within ~1 min, the NEGPCM composites reached 100 °C at the cross area of the sample (where the light was focused to a spot by the Fresnel lens). This is clear from the color-coding of the IR image (Fig. 8), which reveals white-yellowish color at the focused spot indicating a high temperature as compared to its surroundings with blue color indicating a lower surrounding temperature. Our experimental observations of drastic reduction of melting time (rapid thermal charging) of NEGPCM composites under solar illumination could be attributed to the combined effect of plasmonic heating of uniformly dispersed carbon nanomaterials and the conventional thermal diffusion based approach.

It is important to mention that melting and solidification experiments were conducted on pristine paraffin and NG–paraffin composites at 0.5 wt% concentrations of NG, using the conventional heating experimental setup to investigate the heat transfer rate of paraffin and NG–paraffin composites. The melting experiments revealed that the time taken for complete melting of pristine paraffin and NG–paraffin composites at 0.5 wt% NG were 21 min and 15 min, respectively. This represents an overall enhancement

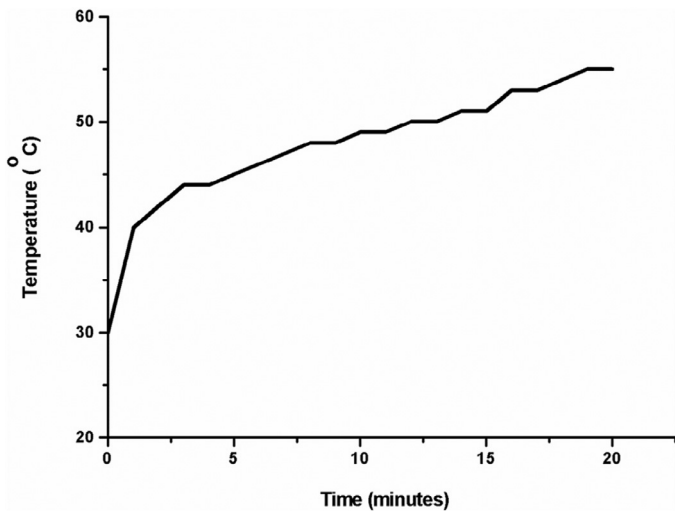


Fig. 9. Temperature distribution of water during charging process (flow rate of water is 0.33 L/min).

of 29% in the melting rate of the NG–paraffin composite compared to that of pristine paraffin under conventional heating approach. This can be attributed to the presence of highly conductive nanographite in the composite. Drawing an analogy from the above results, it is expected that the melting rate of NEGPCM composites would be considerably higher (enhancement $\sim 29\%$) than eutectic gel PCM (EGPCM) under conventional heating setup.

Therefore, on comparing the solar illumination experimental results with conventional heating based results on NEGPCM composites, we conclude that upon solar illumination, the NEGPCM composites demonstrated a drastic enhancement in the melting rate (~ 3 minutes) than the conventional heating based approach. The ultrafast and uniform heating of NEGPCM composites upon solar illumination has been attributed to instant optical charging via plasmonic heating of carbon nanomaterials (NG) in addition to conventional thermal diffusion, which relies on the slow thermal heating from the hot zone to the rest part of thermal storage media (NEGPCM).

3.4. Solar water heating

One of the potential applications of solar thermal energy is solar water heater (SWH). In the present experimental study, NEGPCM composite was used in a solar water heating system to analyze its performance for solar water heating application. As described in the experimental section, SWH heating experiments were carried out using experimental setup shown in Fig. 2.

3.4.1. Results on SWH system

Upon solar illumination, the NEGPCM composite absorbs solar energy and rapidly converts the solar energy into thermal energy due to the plasmonic heating effect of carbon nanoparticles [29,34]. As the charging proceeds, the NEGPCM composite stores energy in the form of latent heat as the composite melts at a constant temperature ($53 \pm 0.5^\circ\text{C}$). During the charging period, as the cold water is circulated through the TES unit, it absorbs the thermal energy from copper pipes via NEGPCM and hot water is generated. A typical water flow rate of 0.33 L/min has been maintained in our experiment. The experimental results during the charging of PCM in SWH system are presented as a graphical representation in Fig. 9, which represents the temperature variation of water inside the storage tank for a mass flow rate of 0.33 L/min. It is observed from Fig. 9 that the temperature of water increases gradually until it reaches the temperature of 55°C and it takes about 20 minutes

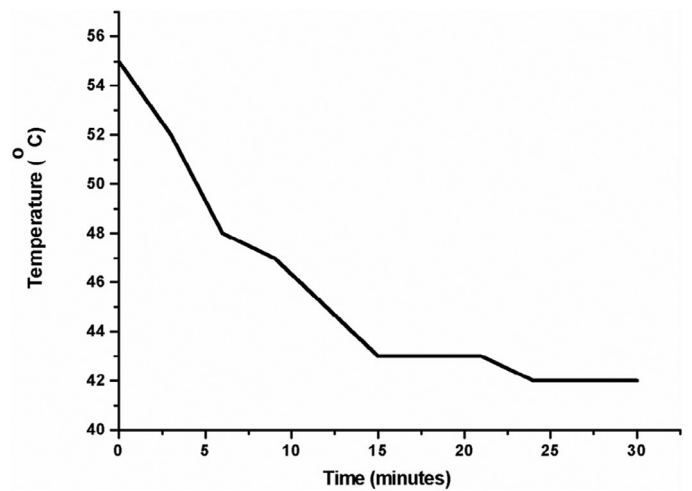


Fig. 10. Temperature distribution of water during discharging process (flow rate of water is 0.33 L/min).

to reach this temperature. It is important to note that our designed hot water system is different from the hot water system developed by other researchers. For example, Rabin et al. [35] developed an integrated PCM solar collector for a low-temperature solar domestic hot water system using salt hydrate eutectic mixture (48% CaCl_2 , 4.5% KCl , 0.4% NaCl and 47.1% H_2O) where the PCM is held inside the collector and thermally discharged to cold water flowing through a heat exchanger. During the discharging process, the lid of the TES unit is closed to prevent the phase change energy of NEGPCM from leaking out and the temperature of water flowing out is monitored. The experimental result during the discharging of heat by PCM system is presented and its graphical representation is shown in Fig. 10. During discharging process, the initial temperature of hot water is 55°C which reaches 42°C after 30 minutes. This clearly shows that the rate of discharging of heat by NEGPCM composites is slower as compared to the charging rate of NEGPCM composites. In other words, the use of NEGPCM composites in SWH system helps to increase the charging time whereas it helps to reduce the discharging time. This is advantageous since it leads to the maximum utilization of solar energy and hence a great improvement in the efficiency of SWH system.

4. Conclusions

A novel eutectic phase change material (PCM) nanocomposite has been prepared through a simple melt mixing process. The prepared NEGPCM composites demonstrate several unique characteristics, such as remarkable solar energy-harvesting, high light-to-heat conversion, high thermal conductivity, ultrafast thermal charging and a rapid heat transfer property. Addition of only 0.5 wt% of nanographite to eutectic PCMs significantly boosts their thermal conductivity without incurring a large reduction in their latent heat and phase transition temperature. Solar illumination experiments on NEGPCM composites revealed that the melting time of NEGPCM composites was drastically reduced to 3 minutes. This represented an overall enhancement of 93% in the melting rate of the NEGPCM composite compared to that of eutectic gel PCM. The composites were employed for two different applications: (i) a solar water heating (SWH) system and (ii) an ultrafast solar chargeable glove. It was found that the use of NEGPCM composites in SWH system led to enhancement in the charging rate and a decrease in the discharging rate, which leads to an increase in the overall efficiency of SWH system. A NEGPCM-based solar rechargeable glove was also designed, which could be charged under sunlight using a small glass lens. With proper insulation, the

glove could store and retain latent heat up to 3 hours, which is useful for providing a comfortable and therapeutic level of heat to painful areas on the back or hands as a temporary treatment.

Acknowledgments

The authors thank Dr. Ashok K Chauhan, founder president of Amity University, for his continuous guidance and encouragement. The authors thank other members of the AIARS (M&D) group, Amity University, Noida for their support.

References

- [1] A. Sharma, V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, *Renew. Sustain. Energy Rev* 13 (2009) 318–345.
- [2] L.W. Fan, J.M. Khodadadi, Thermal conductivity enhancement of phase change materials for thermal energy storage: a review, *Renew. Sustain. Energy Rev* 15 (2011) 24–46.
- [3] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, *Prog. Mater. Sci* 65 (2014) 67–123.
- [4] K. Lin, Y. Zhang, X. Xu, H. Di, R. Yang, P. Qin, Experimental study of under-floor electric heating system with shape-stabilized PCM plates, *Energy Build* 37 (2005) 215–220.
- [5] E. Oró, A.D. Gracia, A. Castell, M.M. Farid, L.F. Cabeza, Review on phase change materials (PCMs) for cold thermal energy storage applications, *Appl. Energy* 99 (2012) 513–533.
- [6] R. Kandasamy, X.-Q. Wang, A.S. Mujumdar, Application of phase change materials in thermal management of electronics, *Appl. Therm. Eng* 27 (2007) 2822–2832.
- [7] J. Yagi, T. Akiyama, Storage of thermal energy for effective use of waste heat from industries, *J. Mater. Process. Technol* 48 (1995) 793–804.
- [8] B. Ying, Y. Kwok, Y. Li, Q. Zhu, C. Yeung, Assessing the performance of textiles incorporating phase change materials, *Polym. Test* 23 (2004) 541–549.
- [9] B. Gin, M.M. Farid, The use of PCM panels to improve storage condition of frozen food, *J. Food Eng* 100 (2010) 372–376.
- [10] D.G. Wood, M.B. Brown, S.A. Jones, D. Murnane, Characterization of latent heat-releasing phase change materials for dermal therapies, *J. Phys. Chem. C* 115 (2011) 8369–8375.
- [11] A. Shukla, D. Buddhi, R.L. Sawhney, Solar water heaters with phase change material thermal energy storage medium: a review, *Renew. Sustain. Energy Rev* 13 (2009) 2119–2125.
- [12] A. Cadet, Process for storing heat with a eutectic composition containing at least one saturated aliphatic hydrocarbon and at least one fatty acid Google Patents, 1982.
- [13] A. Sari, H. Sari, A. Önal, Thermal properties and thermal reliability of eutectic mixtures of some fatty acids as latent heat storage materials, *Energy Convers. Manag* 45 (2004) 365–376.
- [14] J. Zuo, W. Li, L. Weng, Thermal performance of caprylic acid/1-dodecanol eutectic mixture as phase change material (PCM), *Energy Build* 43 (2011) 207–210.
- [15] L.-W. Fan, X. Fang, X. Wang, Y. Zeng, Y.-Q. Xiao, Z.-T. Yu, et al., Effects of various carbon nanofillers on the thermal conductivity and energy storage properties of paraffin-based nanocomposite phase change materials, *Appl. Energy* 110 (2013) 163–172.
- [16] Y. Cui, C. Liu, S. Hu, X. Yu, The experimental exploration of carbon nanofiber and carbon nanotube additives on thermal behavior of phase change materials, *Solar Energy Mater. Solar Cells* 95 (2011) 1208–1212.
- [17] S. Kim, L.T. Drzal, High latent heat storage and high thermal conductive phase change materials using exfoliated graphite nanoplatelets, *Sol. Energy Mat. Sol. Cells* 93 (2009) 136–142.
- [18] J.-N. Shi, M.-D. Ger, Y.-M. Liu, Y.-C. Fan, N.-T. Wen, C.-K. Lin, et al., Improving the thermal conductivity and shape-stabilization of phase change materials using nanographite additives, *Carbon* 51 (2013) 365–372.
- [19] X. Tang, B. Zhu, M. Xu, W. Zhang, Z. Yang, Y. Zhang, et al., Shape-stabilized phase change materials based on fatty acid eutectics/expanded graphite composites for thermal storage, *Energy Build* 109 (2015) 353–360.
- [20] B.E. Jebasingh, Exfoliation of graphite by solar irradiation and investigate their thermal property on capric–myristic–palmitic acid/exfoliated graphite composite as phase change material (PCM) for energy storage, *J. Energy Storage* 5 (2016) 70–76.
- [21] X. Huang, Y.D. Cui, B.N. Zhang, G.Q. Yin, G.Z. Feng, Preparation and properties of capric–lauric–palmitic acid eutectic mixtures/expanded graphite composite as phase change materials for energy storage, *Adv. Mat. Res* 1028 (2014) 40–45.
- [22] A. Sharma, C.R. Chen, Solar water heating system with phase change materials, *Int. Rev. Chem. Eng* 1 (2009) 297–307.
- [23] M.R. Islam, K. Sumathy, S.U. Khan, Solar water heating systems and their market trends, *Renew. Sustain. Energy Rev* 17 (2013) 1–25.
- [24] T.P. Otanicar, J.S. Golden, Comparative environmental and economic analysis of conventional and nanofluid solar hot water technologies, *Environ. Sci. Technol* 43 (2009) 6082–6087.
- [25] S. Mondal, Phase change materials for smart textiles – an overview, *Appl. Therm. Eng* 28 (2008) 1536–1550.
- [26] B. Pause, Development of heat and cold insulating membrane structures with phase change material, *J. Coated Fabrics* 25 (1995) 59–68.
- [27] R. Kumar, M.K. Misra, R. Kumar, D. Gupta, P.K. Sharma, B.B. Tak, et al., Phase change materials: technology status and potential defence applications, *Def. Sci. J.* 61 (2011) 576–582.
- [28] S. Pincemin, R. Olives, X. Py, M. Christ, Highly conductive composites made of phase change materials and graphite for thermal storage, *Solar Energy Materials & Solar Cells* 92 (2008) 603–613.
- [29] A. Kardam, S.S. Narayanan, N. Bhardwaj, D. Madhwal, P. Shukla, A. Verma, et al., Ultrafast thermal charging of inorganic nano-phase change material composites for solar thermal energy storage, *RSC Adv* 5 (2015) 56541–56548.
- [30] A.J. Purvis, N.T. Cable, The effects of phase control materials on hand skin temperature within gloves of soccer goalkeepers, *Ergonomics* 43 (2000) 1480–1488.
- [31] M. Li, A nano-graphite/paraffin phase change material with high thermal conductivity, *Appl. Energy* 106 (2013) 25–30.
- [32] A.R. Akhiani, M. Mehrali, S.T. Latibari, M. Mehrali, T.M.I. Mahlia, E. Sadeghinezhad, et al., One-step preparation of form-stable phase change material through self-assembly of fatty acid and graphene, *J. Phys. Chem. C* 119 (2015) 22787–22796.
- [33] F. Yavari, H.R. Fard, K. Pashayi, M.A. Rafiee, A. Zamiri, Z. Yu, et al., Enhanced thermal conductivity in a nanostructured phase change composite due to low concentration graphene additives, *J. Phys. Chem. C* 115 (2011) 8753–8758.
- [34] A.M. Nemilentsau, S.V. Rotkin, Vertical single-wall carbon nanotube forests as plasmonic heat pipes, *ACS Nano* 6 (2012) 4298–4304.
- [35] Y. Rabin, I. Bar-Niv, E. Korin, B. Mikic, Integrated solar collector storage system based on a salt-hydrate phase-change material, *Sol. Energy* 55 (1995) 435–444.