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Research paper

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

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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.

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 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 $CH_3(CH_2)_{2n}COOH$, 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

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˜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 nighttime 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].