



Fast charging of thermal energy storage systems enabled by phase change materials mixed with expanded graphite



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ABSTRACT

Solar thermal energy harvesting, storage and conversion are crucial parameters to have an effective renewable energy technology that can lead to sustainable and grid-independent technologies as well as lessening of global carbon footprints. Phase change materials (PCMs) are capable of storing and releasing great amounts of thermal energy through utilization of latent heat of fusion as result of material phase change. PCM suffers mainly from low rate of response to demand that is mainly due to low thermal conductivity of PCMs. This drawback could be improved by mixing the PCMs with matrix of high thermal conductive materials. The purpose of this paper is to test the efficacy of expanded graphite (EG) matrix combined with PCM at various percentages of 0–90% by volume in terms of response rate to demand and energy storage capacity PCM-EG composite samples were designed and prepared, and tests were performed under controlled solar radiation (using solar simulator) to study the heating cycle. Temperature data were recorded by means of thermocouples and infrared camera. Time-dependent results were analyzed under various testing conditions. The results show that the tested 80% EG-20% PCM composite showed 7 times faster response rate to charging when compared to 10% EG and 90% PCM mixture, while about 30% energy storage reduction was observed as the penalty. There must be a sweet spot where response rate improvement and energy storage reduction are at their optimum condition for a particular application.

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1. Introduction

With the fast growth of the human population and fuel depletion concerns, the utilization of various forms of renewable energy, including solar thermal energy, have been gaining significant attention. The photo-thermal conversion, the conversion process associated to the photonic energy into thermal energy, is an efficient method for the storage of solar thermal energy with various profits such as high conversion efficiency, affordability, and low cost [1,2]. Thermal energy storage (TES) system with quick response to the demand can be a significant asset in various residential and industrial uses including air conditioning peak load shaving and industry process heating and cooling applications [3–8]. Among various materials used in TES systems, organic materials possess reasonable characteristics such as high energy-storage density, low cost, chemical stability and non-erosiveness [6–8] that make them attractive materials for TES applications. The slow rate of thermal transport inside these organic materials that is connected to their low thermal conductivities has become

a severe limiting factor to their further progression and implementations in real-world applications. To address this dilemma, researchers investigated various methods including high thermal conductivity fillers like metallic particles [9], metal oxide particles [10], graphite [11–13], carbon nanotubes/nanofibers [14–17], graphene [18], and graphene oxide [19,20] to enhance the total thermal conductivity in an attempt to enhance the TES system response rate. In addition to improving the thermal conductivity of phase change materials (PCMs) inside TES systems [21], the direct conversion of solar radiation collection to thermal energy storage has gained significant attention in recent years [15,17,22–26]. Formerly, visible-light harvesting thermal storage materials were prepared by integrating organic dye molecules into poly matrix in order to absorb visible light and then convert it into heat [22,23]. More recently, Wang et al. [27] compared the photo-thermal conversion productivity among gold (Au) nanoparticles (NPs), PbS NPs, organic dyes, and carbon black at the identical mass concentration within water solution. They, in turn, found that small size Au NPs had excellent performance in the sense of conversion efficiency and conversion stabilities [27].

PCMs can be categorized into two major groups of inorganic and organic blends [28]. The majority of inorganic PCMs have the

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benefit of high latent heat capacity at a relatively low cost. However, in many cases they experience some flaws like corrosivity, segregation, and sub-cooling [29]. Despite the fact that organic PCMs generally lack the previously mentioned defects inherent in inorganic mixtures, and have good stability and relatively high latent heat, they possess low thermal conductivity [30]. To improve the properties of PCMs, researchers compounded PCMs with a porous matrix to fabricate a form-stable composite of PCMs [31–35]. Within these form stable composites, the liquid leakage throughout the solid–liquid phase change procedure can be efficiently prevented/minimized by the surface tension forces and capillary of the porous matrices [31,35,36]. Compared with the high temperature heating process, microwave irradiation can be performed at room temperature in a very short time with less energy-consuming, and has been used to prepare exfoliated graphite [37,38]. Zhang et al. [39] tested PCM and expanded graphite (EG) at various selected combinations. They explored the structure stability, photo-thermal performance, and the thermal reliability. The testing did not analyze and report the extensive range of EG-PCM heat storage-per-volume rates and the charging details under sunlight illumination. The graphite surface area can be significantly increased by exfoliation. Compared with the high temperature heating process, microwave irradiation can be performed at room temperature in a very short time with less energy consumption [37–39].

According to the provided literature, there is still lack of understanding on fabrication, testing and analysis of wide varieties of PCM-EG composites as TES systems when used in photo-thermal conversion applications. To address this knowledge gap, this paper reports the in-house exfoliation process of the commercial off-the-shelf (COTS) graphite materials that are used to fabricate PCM-EG composites. The microstructure of the PCM-EG composite were studied and the structural and thermal stability of composites were analyzed and discussed. Finally, the enhanced response rates of the TES systems using the proposed technology were reported and discussed.

2. PCM-EG composite preparation and characterization

Expandable graphite (Intumescent Flake Graphite) powder with a rate of 300 ml/g (Asbury Carbons Co. Ltd., USA) was irradiated using a domestic microwave oven (Hamilton Beach, USA) with an overall power of 1000 W to yield the EG. Exfoliation of the flake graphite results in an overall decrease in bulk density and an approximately 10 fold increase in surface area (Asbury Carbons Co. Ltd., USA).

Technical grade paraffin (Entropy Solutions, LLC, USA) with an engineered phase change transition temperatures between -40°C and 151°C was utilized as the PCM with a melting temperature of 48°C (Table 1). The liquid PCM was procured from melting the paraffin at 60°C . The PCM-EG combinations were produced by absorbing the liquid PCM into the EG. The homogeneous composi-

Table 1
PCM Technical Information (Entropy Solutions, LLC, USA).

Parameter	Value (Unit)
Melting point	48 ($^{\circ}\text{C}$)
Heat storage capacity	230 (J/g)
Thermal conductivity (liquid)	0.15 (W/m $^{\circ}\text{C}$)
Thermal conductivity (solid)	0.25 (W/m $^{\circ}\text{C}$)
Density (liquid)	0.82 (g/ml)
Density (solid)	0.90 (g/ml)
Specific heat (liquid)	2.27 (J/g $^{\circ}\text{C}$)
Specific heat (solid)	2.10 (J/g $^{\circ}\text{C}$)

Table 2
PCM and EG volumetric percentages for each sample.

PCM-EG Sample	PCM (vol.%)	EG (vol.%)
1	100	0
2	90	10
3	70	30
4	50	50
5	30	70
6	10	90

tion of PCM-EG composites at 0% (Pure PCM as baseline), 10%, 30%, 50%, 70%, and 90% by vol.% of EG were prepared. The details of the prepared samples are tabulated in Table 2. Because of having constant volume of container, the volume fraction of each component was assumed to play better role to study the effect of adding EG to the PCM.

PCM-EG samples were examined by using a scanning electron microscope (SEM) (FEI Quanta 200 Environmental Scanning Electron Microscope) equipped with EDAX energy dispersive spectroscopy (EDS). X-ray analysis was performed using a Rigaku Ultima IV diffractometer. Prior to X-ray analysis, the materials were polished to 600 grit. A normal line focus CuK radiation tube was used with power settings of (40 kV, 44 mA). Measurements were made using a D/teX Ultra High-Speed Detector with the detector discriminator set in a fluorescent reduction mode. Diffraction patterns were recorded using a scan speed of 0.01 deg/min using a (sampling width of 0.0002 deg) and a scan range from 80 to 84 degrees.

The flake graphite is capable of expanding which lead to significantly larger surface areas for the same mass of graphite. Fig. 1 shows the SEM images of before and after expansion. It can be observed that how shape of graphite before expansion, Fig. 1(a), and after the expansion in microwave, Fig. 1(b), are changed that leads to larger surface-to-volume fraction. The EG, Fig. 1(b), consists of worm-like microstructure that can be produced from the flattened irregular honeycomb network built from elementary graphite sheets under microwave exposure.

The compound PCM was characterized by XRD to examine the chemical compatibility between the PCM and EG. Fig. 2 performs the XRD trend of the PCM, EG and the sample composite (Typically for Sample 2). As it can be seen in Fig. 2, the XRD pattern of the EG-PCM sample includes all the peaks of PCM and EG, since the peak intensities are relatively different in comparison with those of PCM and EG. The data confirms that the tested PCM-EG composite is only the mixture of PCM and EG, and no other materials has been added. As depicted in past papers [40,41], it is because the PCM paraffin is held by the tension force and capillary force of the porous EG, no liquid PCM is seen on the surface of the sample at the solid–liquid phase change procedure.

In Differential Scanning Calorimetry (DSC) technique, a sample and a reference are kept approximately thorough the testing. The heat capacity of the sample can be analyzed given the known heat capacity of the reference material. Utilizing the DSC technique, the peak melting points and latent heat values of the PCM can be obtained. The DSC results for the tested PCM in this study shows a temperature range of 47–51 degrees of Celsius as the melting region of the PCM is scanned at a rate of 1 $^{\circ}\text{C}/\text{min}$, Fig. 3.

3. Experimental setup and procedure

The photo-thermal conversion apparatus used in this study is shown in Fig. 4. In this experiment, the samples were loaded in the container under the Newport 92250A-1000 solar simulator (Newport Corporation, USA) and then the heat storing process was carried out when the solar simulator light was turned on.

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