Solar Energy 135 (2016) 644–653

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Nanoadditives induced enhancement of the thermal properties of paraffin-based nanocomposites for thermal energy storage

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ARTICLE INFO

Article history:
Received 23 October 2015
Received in revised form 20 April 2016
Accepted 3 June 2016

Keywords:
Nanocomposites
PCM
TES
Thermal enhancement
Thermal solar systems

ABSTRACT

Nanocomposites of a paraffin wax base containing various concentrations (0.5, 1.0, and 1.5 wt.%) of the aluminium, copper, zinc and iron nanoadditives were investigated experimentally and theoretically. The experimental results revealed that an increased weight percent of the additives, within the investigated range, enhanced the thermal properties for TES application. Adding 1.5 wt.% of Cu and Zn nanoparticles enhanced the thermal conductivity of the nanocomposite by 20.6% and 61.5%, respectively. The thermal diffusivity was observed to increase proportionally as the thermal conductivity increases, whereas the specific heat decreases. The experimental results were compared with existing models, and they disagreed with the prediction results of the thermal conductivity values for all of the models in the literature. The Maxwell and Hamilton-Crosser models predicted the closest values to the experimental results; however, they underpredicted the thermal conductivity of the nanocomposite, whereas the values from the other models significantly overpredicted the thermal conductivity values. The collector efficiency performance was enhanced by 15.5% when integrated with PCM-TES. A further enhancement was reported when the collector system was integrated with nanocomposite-TES. The enhanced PCM nanocomposites exhibited improved thermal energy storage capability, mainly in solar/TES integrated applications.

1. Introduction

Thermal conductivity is a key thermal-transport phenomenon in materials and a major thermophysical property requirement in thermal energy storage Joulin et al. (2011). Phase change materials (PCM) such as organics, inorganics and eutectics are mostly used in thermal energy storage (TES) applications. PCMs are widely used in different TES applications such as thermal storage for shifting the peak heat load, indirect-contact latent-heat thermal storage of solar energy and thermal storage with a direct-contact heat exchanger. The use of multiple PCMs with various thermophysical properties has been considered by researchers in cooling and heating applications but with limited success according to the work of Verma and Singal (Verma and Singal, 2008). The study of thermal energy storage system which combine active and passive triple PCM to solve the limitation of the energy storage was conducted by Haosho et al. (2014). In addition, study was carried out on the use of additives on the micron scale to improve the thermophysical properties of PCMs without attaining the desired heat-transfer properties (Haosho et al., 2014). Among the class of PCMs, paraffin belongs to the organic group that is readily available and mostly used in TES. The low thermal conductivity of paraffin affects the gain and release rate of the thermal energy when used for thermal storage in TES. The TES system requires an effective absorptive and storage medium for use in the various thermal energy applications in heating and cooling. The TES system relies on the amount of energy absorbed and released and the internal energy of the material (latent and sensible heat). Hence, TES can be improved by improving its thermal conductivity as reported by Farid et al. (2004).

Experimental and theoretical investigations have demonstrated that, when effectively dispersed in a fluid or a composite, nanomaterial can alter the thermophysical properties to meet the specific requirements for various thermal-energy applications. Roget et al. (2013), investigated the properties of mixed eutectic compositions of solid-liquid PCM comprises $LiNO_3$—KNO_3 and $LiNO_3$—KNO_3-—$NANAO_3$. They used Differential Scanning Calorimetry (DSC). Their experimental measurement doesn't include the thermal properties like the thermal conductivity and the specific heat. They presented the melting points of the compositions, and the densities of the compositions. Fan and Khodadadi (2012) investigated cyclohexane-based Ne-PCM samples prepared with copper oxide

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http://dx.doi.org/10.1016/j.solener.2016.06.008

nanoparticle with various mass concentrations. Their results showed that, in the liquid phase, the samples were enhanced with increasing concentration of nanoparticles, whereas the solid phase exhibited a nonmonotonic enhancement when the concentration was greater than 2%. The thermal conductivity of the ethylene glycol and propylene used as the base fluid in a traditional heat exchanger were enhanced by 38.7% and 40.2%, respectively, when they were mixed with aluminium nitride nanoparticle (AlNs) as reported in the research by Yu et al. (2011). In the report of Colangelo et al. (2012), they concluded that the efficiency of the automotive engine-cooling system increased with the use of an Al_2O_3 water-based nanofluid, used under steady-state conditions. The Al_2O_3 nanofluid increased the efficiency of the cooling system by 30% with 1% volume fraction additive. The effect of adding carbon nanomaterial on the thermal conductivity of liquid paraffin-based suspensions was investigated by Yu et al. (2012). The results showed that the thermal conductivity of the suspensions increases with increasing loading of the carbon additives and that the extent of relative increase depends strongly on the size and shape of the additives. In the study by Al-Kayiem et al. (2013), thermal energy storage system integrated with collector system can increase the heat transfer performance and overall system efficiency. In addition, the use of nanocomposite in the thermal collector storage can increase thermal conductivity of paraffin – PCMs. in a collector system.

Several studies have been conducted to analytically predict the thermal conductivity of nanocomposites and nanofluids using existing or modified models. Eapen et al. (2010) reported that the most common models for this aim are the Maxwell model, Bruggeman's model, Hamilton and Crosser model, Jeffrey model, and Davis model. The huge gaps in the enhancement of the thermal conductivity between the experimental and analytical values obtained in most studies conducted are still unexplainable to a reasonable extent despite various hypotheses suggested by researchers. The main hypothesis presented for the anomalous increase in the thermal-conductivity properties of nanofluids and nanocomposites are Brownian motion of the particle, molecular layering of the liquid at the liquid/particle interface, heat transport by phonon transfer within an instantaneously formed macro-assembly of nanoparticles and the heat conduction clusters of the particles Eapen et al. (2010) and Das et al. (2006). An anomalous increase in the thermal conductivity of nanomaterials dispersed in a base fluid (liquid) or composite (solid) was reported by Kole and Dey (2013). Experimental investigation of Al_2O_3 and CuO nanofluids has been performed by Sundar et al. (2013), as additives to ethylene glycol (EG) and water (W) mixture-based experiments at various loading temperatures. The results showed that, at the same volume concentration and temperature, the CuO nanofluids thermal conductivity was higher than that of the Al_2O_3 nanofluid at a mixing fraction of 50:50% by weight of EG/W.

Many researchers have reported experimental studies on the thermal conductivity of nanofluids, and most of the reports have focused on metal oxides and nanotubes as additives. Among the metal oxides, the oxides Al_2O_3 and CuO are the most well-known nanoadditives used by researchers in their experimental works according to the report of Teng (2013). The crystallization kinetics properties and phase change properties of the nano-composites were studied by Hu et al. (2014), using a solid – solid phase change material Pentaerythritol (PE) with nano-additive of aluminum nitrate used as self-nucleating agent. The phase change experiments showed that the solid-solid phase change temperature of bulk PE with 3.0 wt.% fraction of nano-AIN composite in cooling process was in accordance with that in the heating processes without super-cooling. The enhancement of convective heat transfer in a solar collector systems using encapsulated phase change materials (EPCMs) in which heat transfer fluid (HTF) will pass through the EPCM capsules was carried out experimentally and numerically by Zheng et al. (2015). The test section with the EPCM capsules successfully demonstrate the ability to transfer thermal energy to and from a transport fluid, achieving energy storage and retrieval in multiple charging and discharging cycles.

The experimental investigation on thermal enhancement of an integrated solar collector using PCM – nanocomposite was carried out by Al-Kayiem and Lin (2014), paraffin wax as a PCM and a nanocomposite of paraffin wax with 1.0 wt.% of 20-nm sized Cu-nanoparticles were tested as the energy storage medium for TES. The solar thermal conversion efficiency study was conducted by Chen et al. (2015). While the study of Sari et al. (2015), utilized a series of micro/nano capsules of polystyrene (PS)/tetracosane (C24) –octadecane (C18) eutectic mixture synthesized as encapsulated phase change material (PCM) using emulsion polymerization method.

In this article, the results from experimental measurements on the thermal-conductivity, thermal diffusivity and heat capacity enhancement of nanocomposites are presented and discussed. Most of the previous studies focused on nanofluids with water, ethyl-glycol, and oil bases, whereas paraffin wax is selected as the base material for the nanocomposites investigated in the present work. Selection of wax paraffin as base material is mainly to produce PCM nanocomposite. The experimental findings are compared with the effective thermal conductivities of metal nanoparticles, which are predicted using the existing correlations in the literature. In the present work, nano scale Cu, Zn, Al and Fe were dispersed in paraffin-based nanocomposites using the thermal constant analyzer to measure thermal conductivity values. In addition, the laboratory analysis is used as feed-on parameter to the outdoor experimental analysis. The outdoor experimentation involves three distinct case study used in determining the thermal behavior of the solar collector system.

2. Thermal condcutivity models

There are quite numbers of analytical models developed to predict the effective thermal conductivity of composite materials. The predictability of the various proposed models depends on the underlying mechanism and assumptions employed in the models. In this report, the classical effective medium theory (EMT) based models are employed. Wen and Ding (2004) concluded that the classical models are static models with assumptions of motionless particles and diffusive heat transfer in both continuous matrix phase and dispersed phase. Note that effective thermal conductivity determination takes place in phase transition. The nanofluid and nanocomposites are referred to as the liquid and solid state of the polymer nano-matrix.

The Maxwell model is the most common among the EMT models and many numbers of models are developed from Maxwell models, Trisaksri and Wongwises (2007). Other known EMT models for determination of analytical values of thermal conductivity includes the Bruggeman, Jeffery, Davis and Hamilton–Crosser models. Possible enhancement mechanics for the underlying increment in the thermal conductivity are the Brownian motion effect, molecular surface layering effect, heat transport and heat conduction. Table 1 shows the summary description of the common EMT models which are considered in the present investigation.

2.1. Prediction of the performance enhancement

The thermal conductivity of PCM nanocomposite percentages enhancement were referred as Gupta and Kennel (2010),

$$\text{Percentage of enhancement} = \left[\frac{k_{mixture} - k_{purewax}}{k_{mixture}}\right] \times 100 \qquad (1)$$