Solar Energy Materials and Solar Cells 172 (2017) 82–92

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

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

Advancement in phase change materials for thermal energy storage applications

Karunesh Kant*, A. Shukla, Atul Sharma

Non-Conventional Energy Laboratory, Rajiv Gandhi Institute of Petroleum Technology, Bahadurpur, Jais 229304, Uttar Pradesh, India

ARTICLE INFO

Keywords:
PCM
Latent heat
Sensible heat
Thermal conductivity
Nano-particle

ABSTRACT

In recent years the thermal energy storage applications with phase change materials have attracted wide interest. This has motivated a number of R & D efforts to develop novel materials and design new applications based on PCM. The efficient design of the new applications majorly depends on the quality of PCM employed. Numbers of reviews, reports have been written to compile the wide range of PCMs made available for different applications. This paper focuses on the development of next generation PCMs through the enhancement of thermophysical properties namely thermal conductivity, latent heat of fusion and sensible heat. The paper presents a detailed review of the research updates in this direction so as to produce PCMs with enhanced efficiency in terms of thermal energy storage and efficient heat transfer.

1. Introduction

The fast global economic development has led to a rapidly increasing energy demand. However, conventional fossil fuel energy sources are limited, and their increased usage is adversely affecting ecology due to the emission of harmful gasses, which are supposed to be responsible for climate changes and environmental pollution. Currently, thermal energy storage systems have become one of the necessary means for reducing reliance on the fossil fuels and contributing to a more efficient environmental friendly energy use by utilizing waste heat from solar and other energy sources. Thermal energy storage can be stored by using latent heat storage or sensible heat storage or both. To store and release thermal energy passively, sensible heat storage has been used for centuries. The Larger volume of material is required to store the same amount of energy in sensible heat storage as compared to the latent heat storage (LHS) material. All over the world, the researchers are in search of new and renewable energy sources. One of the routes is to advance energy storage devices, which are as important as developing emerging source of energy. To store energy in suitable forms that can conventionally be converted into the required form is a present-day challenge for the technologists. The thermal energy storage not only reduces the gap between energy supply and demand but also upsurges the performance and reliability of the systems and plays an important role in conserving the energy [1–3].

Amongst above thermal heat storage methods, latent heat thermal energy storage is predominantly more attractive than other modes, owing to its ability to offer high-energy storage density per unit volume or mass in a more or less isothermal process, i.e., store heat at a constant temperature at a phase-transition temperature of PCM. Thus, PCMs release large amounts of energy upon freezing in the form of latent heat fusion and absorb equal amounts of energy from the immediate environment upon melting. Number of PCMs have been investigated by different investigators for different applications [4–15]. R & D efforts related to PCM are mainly devoted to developing novel cost-efficient materials as required for different temperature ranges as per the application requirements. However, last decade has seen serious efforts to enhance the properties of these PCMs, so as these are more efficient and cost effective. In the following section, we discuss the advancement of PCM properties through different methodologies. Though most of these techniques are still under R & D stage, yet some of these have potential to be commercialized in near future.

2. Advancement in PCMs properties

It has been studied that PCMs come in different types, varying from inorganic salts to liquid metals, and can be applied for diverse applications, such as spacecraft design to domestic hot water tanks. However, for implementation, all of the PCM of different categories and for different applications, share certain characteristics and challenges. Of course, the main characteristic of all PCMs is that they transit from solid to liquid over the extent of the operating time. Without this phase transition, the latent heat would not be utilized, and the energy storage or thermal control would rely solely on sensible heating. These properties of the PCM need to be enhanced in an optimized manner, so as

* Corresponding author.
E-mail addresses: k1091kant@gmail.com (K. Kant), amritanshu.shukla@gmail.com (A. Shukla), asharma@rgipt.ac.in (A. Sharma).

http://dx.doi.org/10.1016/j.solmat.2017.07.023
Received 5 February 2017; Received in revised form 6 April 2017; Accepted 18 July 2017

the PCM become more efficient and cost effective. This leads to the enhancement of thermal conductivity, latent heat, and specific heat so that the material under consideration could effectively transfer the heat and can store more thermal energy during phase transition. This could be done either adding some additives to PCM or by designing the application, especially the confinement of PCMs appropriately. Recent studies related to such efforts are discussed below.

2.1. Thermal conductivity enhancement

In spite of the great advantages, most PCM's have a limitation of their own i.e., very low thermal conductivity [16]. To reduce the thermal energy charging/discharging time of TES system and temperature difference, enhancing the thermal conductivity of PCM is one of the ways to improve the effectiveness of the PCM-based TES systems. As a result, a number of researchers have attempted to increase the performance of TES- PCM, as a priority research in recent past [17]. This includes the introduction of high conductive metal fins and fibers in various forms such as fins, honeycomb, wool, and brush, and the addition of different additives to enhance the thermal conductivity of PCM [18,19].

2.1.1. Insertion of stationary metallic structure

Biwole et al. [20] carried out an experimental and numerical study on photovoltaic panel performance improvement using PCMs. The numerical study based on a validated thermal model with and without aluminum fins, within the container, showed that the temperature of photovoltaic panels was maintained at a lower temperature when using aluminum fins. Kousksou et al. [21] carried out a numerical study on melting of gallium over a wavy surface in a rectangular cavity heated from below. The detailed investigation was carried out for the flow structure and heat transfer characteristics with the effect of the amplitude of the wavy surface and it was found that the rate of the melting upsurges with the elevation in the magnitude of the amplitude value of the wavy surface. Pakrouh et al. [22] presented a numerical investigation on geometric optimization of PCM-based pin fin heat sinks. Paraffin RT-44 HC is used as PCM while the fins and heat sink base are made of aluminum. The main goal of the study was to obtain the configurations that maximize the heat sink operative time. Taguchi method coupled with numerical simulations was applied for this purpose. Fins height, thickness, the number of fins and the base thickness were constraints which were studied for optimization. The conduction and convection controlled heat transfer with volume variation during the melting process were considered in the simulations. Optimization was carried out for different critical temperatures of 50 °C, 60 °C, 70 °C and 80 °C and results showed that a complex relation exists between PCM and thermal conductivity enhancer volume percentages. The optimal case strongly depends on the fin's number, height, thickness and also the critical temperature. Mustaffar et al. [23] proposed to use expanded metal mesh (EMM) as a cheap alternative to improve the performance of the energy storage systems. The 90% porosity was created using raised aluminum EMM sheet, which was cut into five layers, arranged vertically and attached to wire columns. Salt hydrate having melting temperature 46 °C, filled the void space creating a PCM/EMM composite and heated at 55 °C. The melting completion time of PCM with EMM was reduced by 14% and it could increase the better thermal interfaces if soldering and brazing were applied. The thermal modeling of PCM/EMM was in good agreement with the experimental results, which verified its possibility to model PCM/EMM systems. The simulation results showed that properly connecting EMM layers arranged in parallel, caused an 81% melting time reduction. EMM is a promising concept in augmenting heat transfer rate in PCM, which needs additional studies to optimize the performance of thermal energy storage system. An experimental and theoretical study of the unidirectional freezing of water as a PCM filled in metal foams had been carried out by Feng et al. [24]. A detailed concern was made upon determining in what technique the contact conditions between the metal foam and the cold wall effect the freezing process, as well as exploring the local thermal stability concerning the metal foam and the PCM. There were three contact conditions were considered, i.e., applied pressure, natural contact, and bonding with a high thermal conductivity adhesive was addressed these queries. To discover the local thermal equilibrium, the temperatures on foam ligaments and within the pores were measured distinctly by means of thermocouples. The above-mentioned contacting conditions were found to have a similar freezing rate for the current copper foam/water PCM system. This specified that in practice one can only embed metal foam blocks into PCMs with no need of bonding them to the cold wall via a sintering thermal adhesive, or another method, so reducing the costs of devices in energy storage systems.

2.1.2. Addition of metallic nanoparticle

Ebrahimi et al. [25] carried out a numerical study on melting of a nano-enhanced phase change material (NePCM) in a square cavity with two heat source–sink pairs in three different percentage (0%, 2%, 5%) of nanoparticles. Four different cases were studied: Case I where the heat sources and sinks were separately positioned on two vertical sidewalls of container; Case II where the heat sources and sinks were alternately placed on two vertical sidewalls; Case III where the heat sources were placed below the sinks on the vertical sidewalls; and Case IV where the heat sources were placed above the sinks on the vertical sidewalls. It was investigated that Case II had the highest liquid fraction and case IV possesses the lowermost liquid fraction at the final phases of the melting process. Furthermore, the impacts of the nanoparticle loading were analyzed. In all the cases studied in the present study, the volumetric concentration of nanoparticles of 2% would result in the highest melting rate. Fan et al. [26] presented a technical report on the similarity solution to a two-phase, one-dimensional, three-region Stefan problem, through use to unidirectional solidification of nano-enhanced phase change materials (NEPCM) in a semi-infinite domain accounting for the incidence of a mushy region. The NEPCM were considered as homogeneous combinations with effective thermo-physical properties by ignoring diffusion of the nano-additives. NEPCM consisting of Dodecanol and Graphene nanoplatelets, as the base PCM and nano-additives respectively were studied. The comparative solidification rate was compared quantitatively; viewing that solidification was greatly accelerated up to a factor of 34% at the maximum loading of 1.0 wt%. On the basis of the similarity solution, thermal conductivity improvement of the NEPCM was deduced to be the major cause leading to expedited solidification. Tasnim et al. [27] report thermal performance of porous latent heat thermal energy storage (or LHTES) system filled with nanophase change material (or Nano-PCM). First of all the scale analysis was carried out to estimate the extent of the complete phase transition process that is a significant matter to design LHTES systems. The results of the dimensional analysis have simplified the relations among different non-dimensional parameters (i.e., Stefan number, Fourier number, Nusselt number, Rayleigh number, the porosity of the porous medium, and nanoparticle volume fraction). In the second part of the study, the natural convective heat transfer during the melting of nanoparticle-dispersed PCM inside the porous medium was solved numerically. The Darcy model was applied to the porous medium. The numerical simulation of nano-enhanced phase change materials was carried out for the two purposes. The first was it confirms the accuracy of the relations proposed by dimension analysis and second was it ascertains the effects of nanoparticle volume fraction, time, and Rayleigh number, on the thermal field, flow field, and heat transfer procedure through the melting of nanoparticle enhanced PCM within thermal energy storage system. The suggested relations can be applied to forecast the progress and execution of LHTES system packed with porous medium saturated by nano-particle dispersed PCM. Hosseinizadeh et al. [28] presented a numerical investigation of unconstrained melting of NEPCM within a spherical container using RT-27 and copper particles as a base material and nanoparticle, respectively. The numerical