International Journal of Thermal Sciences 91 (2015) 49–58

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Energy storage system based on nanoparticle-enhanced phase change material inside porous medium

Rakib Hossain [a], Shohel Mahmud [a], Animesh Dutta [a], Ioan Pop [b,*]

[a] *School of Engineering, University of Guelph, Guelph, ON, Canada*
[b] *Department of Mathematics, Babeş-Bolyai University, 400084 Cluj-Napoca, Romania*

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form
30 December 2014
Accepted 31 December 2014
Available online

Keywords:
Energy storage
Fourier number
Nano-PCM
Melt fraction
Porosity
Stefan number
Volume fraction

ABSTRACT

A Nanoparticle-enhanced phase change material contains high thermal conductivity nanoparticles, which are assumed to be dispersed uniformly into the phase change material. The inclusion of the nanoparticles improves the effective value of thermal conductivity of the nanoparticle-enhanced phase change material (or nano-PCM). The effective heat transfer rate of nano-PCM can be improved further by incorporating a porous medium. This is the first paper in this series, which reports thermal performance of an energy storage system filled with a porous medium and the void space inside the porous medium is occupied by a nano-PCM. A 2-D enclosure is considered to replicate energy storage system. Two vertical walls and the bottom wall of the enclosure are properly insulated. The nano-PCM (Cyclohexane + CuO nanoparticle) is considered initially at its melting temperature. The top surface of the enclosure is suddenly exposed to a thermal source having a temperature above the melting temperature of the nano-PCM. The effect of the volume fraction of nano-particle and porosity of the porous medium are studied on temperature distribution, heat transfer, and melt fraction inside the cavity. A two dimensional thermal model is developed for both solid and liquid fractions of the nano-PCM. The modeled equations are solved numerically using initial, boundary, and interface conditions. A scale analysis is executed to establish simplified relationships between different non-dimensional parameters (i.e., Fourier number, Stefan number, porosity, and volume fraction).

1. Introduction

Phase change material (PCM) already exhibits excellent potentials for various applications; for example, energy storage, electronic cooling, and building energy management [1]. PCMs are known for their low thermal conductivities. However, a faster rate of melting/freezing is a requirement for many applications [2]. Therefore, efforts have been made to enhance the rate of melting/freezing by utilizing different methods. An effective method of improving the melting/freezing rate is to incorporate a porous insert (e.g., foams, fins, random structure, and heat sinks) inside the system. Porous insert helps enhancement of thermal energy transport all over the PCM [3]. However, the addition of solid matrix of porous inserts reduces the effective volume of the PCM. Therefore, there is a limit of using the amount of porous insert for a particular application in order to avoid the volume reduction of PCM. A use of high-porosity open-foam type porous material can ensure the minimal volume reduction of PCM. In addition to the porous insert, incorporation of highly conductive nano-particles in PCM (or base PCM) can further enhance the melting/freezing rate of PCM. Such nano-particle enhanced phase change material is called nano-PCM. Nano-particles improve the thermal conductivity of the base PCM and such improvement enhances the heat transport rate [4]. However, excess use of nano-particles in base-PCM can have adverse effect (e.g., heavier fluid, sedimentation, etc.) on the thermal performance of nano-PCM based porous media. Therefore, a right combination of porous matrix porosity and nano-PCM volume fraction could be an attractive choice for the optimization of melting/freezing rate.

Phase change materials (PCM) are typically used in the *latent heat energy storage system* where energy is stored in the form of latent heat of fusion during the melting and recovered during the subsequent freezing of the phase change materials for various heat transfer applications. Prediction of such alternating melting-freezing heat transfer processes is an important factor to design optimally any latent heat energy storage system. Many studies are

---

* Corresponding author.
E-mail address: popm.ioan@yahoo.co.uk (I. Pop).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.12.023
1290-0729/

found in the literature about this unique feature of phase change material.

1.1. PCM general application

Phase change materials have been widely utilized for many solar-thermal applications. Typical examples are PCM-based solar water heaters [5–7]. Such systems are typically inexpensive, easy to fabricate, and simple in operation. PCMs are used as single or multiple layers in these systems. Reported performance results on the PCM based air heater systems are also available in the literature [8,9]. Other noticeable solar thermal applications where use of PCMs are getting popularity are solar cooker [10] and green house [11]. PCM and PCM based systems have been utilized for thermal management of buildings and structures. Some applications include energy storing walls [12–15], window shutters [16], passive heating system for floors and ceiling [17–19], and off-peak electric storage [20,21]. PCM is also used to design novel heat exchanger in waste heat recovery applications [22]. As a passive temperature regulator, PCM is also used in solar-PV applications [23–25]. Several authors have reported limited applications of PCM for electronic systems [26–28]. Some other noticeable applications of PCM include air-conditioning and ventilation systems [29], cooling of electric motor [30], and thermal management of batteries and electronic devices [31,32].

1.2. Nano-PCM with non-porous medium

One major issue in the engineering use of PCMs is that most PCMs have poor thermal conductivity as mentioned earlier. Many techniques applied for heat transfer enhancement are found in the literature to overcome PCMs' lower thermal conductivities. Such techniques required to enhance the heat transfer rate include the dispersion of highly conductive nanoparticles, impregnation of PCMs in a porous media such as metal or graphite matrix, the use of fins and finned tubes, the use of agitators, using microencapsulated PCM, use of multiple PCMs, rings in PCMs, which is done by increasing the thermal conductivity in the PCMs without much reduction in energy storage. Among all of these methods, the dispersion of highly conductive nanoparticles along with impregnation of PCM in porous media is the main interest of this research.

Khodadadi and Hosseinizadeh [4] studied the natural convection solidification process numerically inside a differentially-heated square cavity that contains a nano-PCM. They observed that nano-PCM exhibits higher heat release rate when compared to the conventional PCM partly due to simultaneous increase of the thermal conductivity and reduction of the latent heat. Fan and Khodadadi [33] conducted theoretical (modified 1-D Stefan model) and experimental investigations on freezing of nano-PCM in a vertical container. A cooled-from-bottom unidirectional freezing experimental setup was constructed to validate the theoretical result. Ho and Gao [34] experimentally examined the melting process of a nano-PCM (n-octadecane + Al_2O_3) in a vertical enclosure. Ho and Gao [34] reported that the natural convection heat transfer inside the liquid region degrades with increasing nano-particle mass fraction when compared with the natural convection result of the base PCM. Other studies include the transient characterization and identification of the efficiency of thermal energy storage packed with '*microencapsulated phase change material*' [35].

1.3. Impregnation of PCM in porous media

Several authors also reported the thermal enhancement of PCM only inside the porous medium. For example, Zhao et al. [3] performed experimental investigation to characterize the phase change processes (both melting and solidification) of paraffin wax inside the copper metal foam. Their results show that the use of porous medium enhances the solidification and melting process faster than pure PCM without porous medium. Lafdi et al. [36] experimentally observed the influence of convection on the melting process of paraffin wax inside the high thermal conductivity metal aluminum foam with various porosities. Lafdi et al. [36] observed that the metal foam with higher porosity assists convection mechanism while foam with lower porosity assists conduction mechanism. Therefore, the authors recommended that one should select optimum porosity and pore size to utilize both conduction and convection mechanisms effectively for better heat transfer performance.

1.4. Nano-fluid in porous and non-porous media

Buongiorno [37] presented an excellent review on the influence of several effects (e.g., inertia, Brownian diffusion, magnus effect, fluid drainage, gravity, and thermophoresis) on nanofluid convection. The transport processes of nanofluids in porous medium have been a focus of study in recent years. In a series of pioneering articles, Kuznetsov and Nield [38–40] have developed modeling equations to study transport of nanofluid problems inside porous media. The authors have considered that nanoparticles are suspended particles in the base fluid utilizing one of the following technologies: surfactant and surface charge technologies. This could avoid nanoparticles from agglomeration and deposition inside the pore of the porous matrix.

Based on the literature reviewed no published article is identified that considers phase change process of nano-PCM inside porous medium. However, there are considerable numbers of articles which deal with 'nano-fluid transport in porous medium' or 'phase change process of nano-PCM in non-porous medium'. Therefore, authors believe that this is the first article which deals with phase change process (mainly melting) and heat transfer characteristics of a nano-PCM inside porous medium. As this is a pioneering work, authors prefer to make the model and analysis less complicated using simpler models available in the literature. Therefore, non-Darcy momentum modeling, boundary and inertia effect, thermal non-equilibrium modeling, and Brownian motion and thermophoresis effect are not incorporated into the current model. These are left for future works.

2. Problem formulation

Consider a rectangular enclosure, which represents a simplified thermal energy storage system, of width L and height H as shown schematically in Fig. 1(a). The enclosure, bounded by impermeable walls, is filled with a porous medium. Initially, a solid phase of nano-PCM completely fills the void space of the porous medium inside the enclosure. For simplicity of analysis, the initial temperature of the nano-PCM is considered equal to the fusion temperature (T_m) of the nano-PCM. It is assumed that the local thermal equilibrium exists between the nano-PCM and the porous medium. Therefore, at any time, temperatures of the nano-PCM and the porous matrix are equal at any representative control volume. All the walls of the enclosure are properly insulated except the top horizontal wall which is exposed to a heat source having constant temperature but higher than the fusion temperature of the nano-PCM. Because of the temperature gradient, thermal energy will start penetrating through the top wall. Such penetration of the thermal energy will initiate the phase change process (melting) of the nano-PCM inside the porous medium.