Applied Energy 191 (2017) 22–34

Contents lists available at ScienceDirect

Applied Energy

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

Melting enhancement in triplex-tube latent heat energy storage system using nanoparticles-metal foam combination

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HIGHLIGHTS

- Combines nanoparticles with metal foam in a triplex-tube PCM energy storage system.
- Melting time of the PCM is modeled, validated with experiments and studied.
- The combination was found to greatly reduce the melting time of the PCM.
- Allied parameters responsible for improved performance of the system were revealed.

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 6 October 2016
Accepted 9 November 2016
Available online 28 January 2017

Keywords:
Melting
PCM
Triplex-tube
Energy storage
Nanoparticles-metal foam

ABSTRACT

Phase change material (PCM) energy storage systems have relatively low thermal conductivity values which greatly reduces the systems' performance. In this study, a compound porous-foam/nanoparticles enhancement technique was used to significantly improve melting of a phase change material (PCM) in a triplex-tube heat exchanger applicable to liquid desiccant air-conditioning systems. A mathematical model that takes into account the non-Darcy effects of porous foam and Brownian motion of nanoparticles was formulated and validated with previous related experimental studies. The influence of nanoparticle volume fraction and metal foam porosity on the instantaneous evolution of the solid-liquid interfaces, distribution of isotherms, and liquid-fraction profile under different temperatures of the heat transfer fluid (HTF) were investigated. Results show that dispersing nanoparticles in the presence of metal foams results in melting time savings of up to 90% depending on the foam structure and volumetric nanoparticle concentration. Although the melting time decreases as the porosity decreases and/or volume fraction increases, high-porosity metal foam with low volume-fraction nanoparticles is recommended. This ensures minimal PCM volume reduction and promotes positive contribution of natural convection during the melting process.

1. Introduction

Technologies for storing energy are of a great practical importance due to their potential for correcting the mismatch between energy supply and energy demand particularly for intermittent energy sources like solar and wind. The three main methods used for storing energy in TES systems are sensible, latent, and thermochemical. The latent method is more attractive than others due to its relatively high storage density and nearly isothermal storage performance. The phase change materials (PCMs) used as storage media in latent TES systems, can store 5–14 times more energy than sensible storage materials with the same volume [1]. However, most PCMs suffer from undesirable property of relatively low thermal conductivity which strongly suppresses energy charging/discharging rates and makes the system response time too long to meet the requirements. A way to overcome this issue is through modifications in the PCM container structure such as insertion of fins [2], application of heat pipes [3], and/or metal foams [4–11]. One of the more recent ways of improving the thermal conductivity is through dispersion of highly conductive nanoparticles that have nominal sizes ranging from 1 to 100 nm [12–15].

Among the various enhancement techniques available for PCM-based TES applications, metal foams have been shown to be one of the most efficient solutions in terms of the storage improvement [16]. For example, Zhao et al. [5] reported that phase-change rate can be increased by up to 10 times with inclusion of metal foams. Metal foams are porous metallic structures with small openings

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http://dx.doi.org/10.1016/j.apenergy.2016.11.036
0306-2619/

Nomenclature

A_m	mushy zone constant
A_{sf}	interfacial surface area (m^{-1})
C_f	inertial coefficient (m^{-1})
C_p	specific heat (J/kg K)
d_l	ligament diameter (m)
d_p	pore size (m)
g	gravity acceleration (m/s^2)
h_{sf}	interfacial heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	permeability of porous foam (m^{-2})
L	latent melting heat (J/kg K)
P	pressure (Pa)
Pr	Prandtl number
Ra	Rayleigh number
r	tube radius (m)
T	temperature (K)
T_l	liquidus temperature of the PCM (K)
T_s	solidus temperature of the PCM (K)
u	velocity component in r-direction (m/s)
v	velocity component in θ-direction (m/s)
HTF	heat transfer fluid
PCM	phase change material
PPI	pore number per inch
TES	thermal energy storage

Greek letters

ρ	fluid density (kg/m^3)
φ	nanoparticles volume fraction
λ	liquid fraction
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (kg/m s)
ζ	correction factor
ε	porous foam porosity
ω	pore density (PPI)
α	thermal diffusivity (m^2/s)
ν	kinematic viscosity (m^2/s)

Subscripts

np	nanoparticle
e	effective value
f	liquid nanoPCM
i, o	inner, outer tube
int	initial
s	porous foam
w	wall

Superscripts

$\bar{}$	a property for porous nanoPCM

called pores or voids. They are mainly characterized by two parameters: porosity (ε) and pore density (ω). Porosity is the ratio of the void volume to the total volume occupied by the foam and the void space. Pore density is the number of pores per linear inch (PPI). The undesirable characteristic of metal foams is they critically reduce the available PCM volume and consequently cause less overall storage capacity. So, only metal foams with high porosity (⩾90%) are recommended for use in energy storage applications. The high porosity makes the metal foam light in weight, large in void passages, and enhanced in interstitial heat transfer to the PCM due to the formation of thin boundary layers. The heat transfer, as will be proposed later on in this study, can be further enhanced by incorporation of highly-conductive nanoparticles. Studies such as [13,14] have shown that successful dispersion of nanoparticles can enable the PCM to achieve higher thermal conductivity and exhibit better thermal storage performance.

One of the pioneering studies on improving the functionality of phase change materials (PCM) through dispersion of nanoparticles is by Khodadadi and Hosseinizadeh [12]. The study showed that phase-change heat transfer enhancement by nanoparticles is promising for utilization in thermal energy storage systems. Wu et al. [13] experimentally investigated the melting/solidification characteristics of copper/paraffin as nanoparticle-enhanced phase change material. The results revealed that the thermal conductivity of paraffin can be enhanced by the use of copper nanoparticles. The same authors [15] presented numerical simulation studies for melting of copper/paraffin nanocomposites. Sciacovelli et al. [17] studied the thermal behavior of the latent TES unit charged with nano-enhanced PCM. A melting time reduction of 15% was reported by doping nano-enhanced PCM. Arasu and Mujumdar [14] investigated the melting of paraffin wax dispersed with alumina nanoparticles in a square cavity heated either from below or from the vertical side. The study pointed out that the melting rate was higher when the cavity is heated from the side than when heated from below. Lin and Al-Kayiem [18] showed that dispersing copper nanoparticles in paraffin wax not only enhances its thermal conductivity but also improves its thermal stability and reduces its supercooling effect during the discharge phase. Mahdi and Nsofor [19] showed that dispersing alumina nanoparticles of (3–8% by volume) can reduce the solidification time of paraffin RT82 up to 20% in a triplex-tube TES system. Moreover, changing the charging temperature of the HTF from 65 °C to 70 °C does not significantly affect the time savings due to nanoparticles dispersion. Myers et al. [20] dispersed (2% by volume) CuO nanoparticles in three nitrate salts: sodium nitrate ($NaNO_3$), potassium nitrate (KNO_3), and the KNO_3–$NaNO_3$ eutectic. Results showed no chemical degradation under thermal cycling but showed significant improvement in thermal performance of the nano-enhanced salts relative to the pure salts.

Due to the high thermal conductivity, large area-to-volume ratio, and strong mixing capability, porous metal foams (e.g. copper and aluminum) are considered to be one of the most promising heat transfer enhancement materials [21,22]. Lafdi et al. [4] ran experiments to study the effects of porosity and pore size of aluminum foam on melting evolution of paraffin wax as a PCM and found that steady-state temperature can be reached faster in both higher porosity foams and bigger pore sizes. Zhao et al. [5] studied the effects of embedding metal (copper) foam on thermal performance of solid-liquid phase change process of RT58 as a PCM. Results revealed that better phase-change rate can be achieved depending on the metal foam structure and material. Cui [7] showed through an experimental investigation that metal foams embedded in PCMs can enhance heat transfer rate, increase the melting rate and shorten the charging period. Li et al. [8] reported that uniformity of temperature distribution inside paraffin-saturated in copper foams can be augmented either by decreasing pore density to enhance natural convection or by decreasing porosity to improve the effective thermal conductivity. Sundarram and Li [9] numerically studied the performance of PCM infiltrated microcellular metal foams under high heat generation and low