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Melting enhancement in triplex-tube latent thermal energy storage system using nanoparticles-fins combination

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ABSTRACT

Latent thermal energy storage based on Phase Change materials (PCMs) offers a promising solution for correcting the problem of availability of intermittent energy from renewable sources like solar, wind, etc. PCMs have the potential to store large amounts of energy in relatively small volumes and within nearly isothermal processes. However, a major drawback of today's PCMs is that their low thermal conductivity values critically limit their energy storage applications. Also, this grossly reduces the melting/solidification rates, thus making the system response time to be too long. In this study, three enhancement techniques: fins, nanoparticles and a combination of both were investigated with the aim of correcting this limitation. A numerical study based on enthalpy method was used to comparably examine the effects of these techniques on the PCM melting rate in triplex-tube latent heat storage system. A mathematical model that takes into account the natural convection and the Brownian motion of nanoparticles was formulated and successfully validated against previous experimental data. The influence of using different dimensions of fin and different nanoparticle volume fractions on evolution of the solid-liquid interfaces, distribution of isotherms, and temporal profile of liquid fraction over the whole melting process was studied and reported. The results indicate that PCM melting is improved by using these techniques studied. Also it was found that the use of fins alone is better than using either nanoparticles alone or a combination of fins and nanoparticles. The use of longer fins with smaller thicknesses is recommended so as to improve phase-change heat transfer and minimize the volume occupied in the energy storage space.

1. Introduction

Increasing share of renewables like solar and wind for responding to growing global energy demand requires efficient means to correct their intermittent nature. In this regard, thermal energy storage (TES) was found to be a practical choice for broad renewable-based applications, that range from solar water heaters to building air conditioning systems [1]. By definition, TES is the storage of energy in a thermal form for later use. There are three options available for storing energy in TES systems: sensible, latent, and thermochemical. Latent option is more attractive than others due to the relatively high storage density and nearly isothermal nature of the storage process. For example, latent TES using Phase Change Materials (PCMs) can store 5–14 times higher energy than using sensible storage materials for the same volume [2]. However, low thermal conductivity of most PCMs strongly suppresses the energy charging/discharging rates and makes the system response time too long to achieve the desired results. Therefore, many investigations have been conducted to enhance the thermal conductivity of PCMs and many concepts such as insertion of fins [3–9], heat pipes [10], and metal matrices [11] have been proposed. However, the major drawback associated with all those techniques is their extra added weight and/or volume limits flexibility in designing light, small-size storage systems in cases where weight and volume usage are of design concerns. Furthermore, these techniques negatively affect the PCM fluidity during the phase-change and they degrade the positive contribution of natural convection in the associated heat transfer process. A more recent way that can maintain relatively better fluid-like form during the phase-change process is to improve the thermal conductivity through dispersion of highly conductive nanoparticles having nominal sizes ranging from 1 to 100 nm [12–18].

Among the techniques mentioned above, fins come at the top of the list as the most commonly used heat transfer enhancement technique in engineering applications including PCM-based TES

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Nomenclature

A	area
A_m	mushy zone constant
b	fin thickness (mm)
C_p	specific heat (J/kg K)
d_p	pore size (m)
g	gravity acceleration (m/s^2)
k	thermal conductivity (W/m K)
Γ	latent melting heat (J/kg K)
L	triplex-tube length
P	pressure (Pa)
r	tube radius (m)
t	time (s)
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)
V	volume (mm^3)
w	fin length (mm)
HTF	heat transfer fluid
PCM	phase change material
TES	thermal energy storage

Greek letters

ρ	fluid density (kg/m^3)
φt	total volume fraction
φf	fin volume fraction
φn	nanoparticle volume fraction
λ	liquid fraction
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (kg/m s)
ζ	correction factor

Subscripts

np	nanoparticle
npcm	nanoPCM
f	fin
i, o	inner, outer tube
w	wall

applications. Also, heat transfer can be further enhanced through incorporation of highly conductive nanoparticles. As reported by a number of studies (e.g. [13,14]), successful dispersion of nanoparticles will enable the PCM to have higher thermal conductivity and exhibit better thermal storage performance. The concept of incorporating nanoparticles to enhance the thermal response of PCMs has been first introduced by Khodadadi and Hosseinizadeh [12]. The study showed through numerical simulation that phase-change heat transfer enhancement by nanoparticles is promising for utilization in TES applications. Wu et al. [13] experimentally investigated the melting/solidification characteristics of copper/paraffin as a nanoparticle-enhanced phase change material (nanoPCM). The results revealed that with copper nanoparticles of 2% by weight the thermal conductivity of paraffin can be enhanced by 14% in solid phase and 18% in liquid phase. Arasu and Mujumdar [14] numerically investigated heat transfer enhancement by dispersing alumina nanoparticles in paraffin as a PCM and found that nano-enhanced paraffin shows higher melting rate when the cavity is heated from the side rather than from below due to enhanced natural convection effect. Sciacovelli et al. [19] numerically studied the thermal behavior of a vertical shell-and-tube TES unit charged with a nano-PCM. The results indicated a melting time reduction of 15% achieved by doping nanoparticles of 4% volumetric concentration. Chieruzzi et al. [20] dispersed 1 wt.% silica, alumina, and a mixture of silica and alumina nanoparticles in potassium nitrate as a PCM and found that addition of silica nanoparticles has the best potential for enhancing the PCM specific heat and total stored heat. Recently, Mahdi and Nsofor [21] showed via numerical investigation that dispersing alumina nanoparticles of (3–8% by volume) in paraffin RT82 can reduce the discharging (solidification) period up to 20% in a horizontal triplex-tube TES unit.

Due to the effectiveness, relative ease in fabrication, and low cost of construction, metal fins are being considered as one of the most practical heat transfer enhancement techniques [4]. Gharebaghi and Sezai [3] numerically studied a finned heat sink filled with RT27 as PCM in horizontal and vertical arrangements. Results showed that for high temperature differences the heat transfer rate can be increased as much as 80 times by adding fins, and a faster melting can be achieved with decreasing fin spacing. Agyenim et al. [4] used circular-finned, longitudinal-finned and bare tubes in a double-pipe TES system to study charging and discharging of Erythritol as a PCM. The results indicated that the longitudinal fins gave the best heat transfer performance with a reduced subcooling during the discharge. Ismail and Lino [5] experimentally studied solidification of PCM in a TES system with bare tube, finned tube and finned tube with stainless steel wire as a turbulence promoter. The results revealed that the use of the turbulence promoter reduces time for complete solidification but the reductions are less pronounced than those due to the fins. Al-Abidi et al. [7] experimentally studied the phase change of paraffin RT82 in finned triplex-tube TES system for different temperatures and mass flow rates of the heat transfer fluid (HTF). The results indicated that the HTF temperature has more influence on the PCM melting than the HTF mass flow rate. Rathod and Banerjee [8] presented an experimental study on melting and solidification of paraffin as a PCM in vertical shell-and-tube heat exchanger assisted by longitudinal fins. The study reported a reduction in total time of up to 25% in melting and 44% in solidification with installation of fins. Sciacovelli et al. [9] numerically studied the thermal behavior of a shell-and-tube TES system assisted by Y-shaped fins with single and double bifurcations. The results showed that the discharge efficiency increases by about 24% when optimal fins with double bifurcation are used. Darzi et al. [22] used finned-circular, circular and elliptical cylinders to numerically study the melting and solidification of a nanoPCM within a concentric cylindrical annulus. The results showed that changing shape into elliptical, adding nanoparticles or inserting fins all leads to higher phase change rates.

It is worthy to state here that employing enhancement additives such as fins and nanoparticles, to alleviate the poor thermal conductivity of PCMs may lead to loss of storage capacity compared to employing only the pure PCM due to reduction in the PCM volume (or decreased mass of the storage material). This study has used the fin volume fraction (φ_f) along with the nanoparticle volume fraction (φ_n) to study the volume reduction arising from using the fins and nanoparticles for the heat transfer enhancement.

The study attempts to positively combine nanoparticles and fins as a compound enhancement technique to achieve better charging