International Journal of Heat and Mass Transfer 124 (2018) 663–676

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Accelerated melting of PCM in energy storage systems via novel configuration of fins in the triplex-tube heat exchanger

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ARTICLE INFO

Article history:
Received 31 July 2017
Received in revised form 8 January 2018
Accepted 26 March 2018

Keywords:
Energy storage
Fin
Melting
Heat exchanger
PCM
Triplex-tube
Nanoparticles

ABSTRACT

Thermal energy storage with Phase Change Materials (PCMs) can be used to fill the gap between energy supply and demand. The main reason preventing their widespread application is the low thermal conductivity of PCMs which makes the systems to have slow energy storage and recovery rates. This study achieved better PCM melting rate with novel fin configuration in triplex-tube storage compared to the use of nanoparticles. This will eliminate problems such as associated viscosity increases and sedimentation. Since heat transfer at different parts of the unit is not the same, a variety of fin arrangements were investigated with numerical analyses of the PCM melting in the triplex-tube. Significant increases in the rate of PCM melting were achieved using special arrangements of fins. Results show that using long fins at the lower half of the storage unit where conduction dominates resulted in accelerated melting. It was further found that using fewer and relatively shorter fins at the upper half of the unit results in better performance. Using this arrangement in the storage unit containing pure PCM achieved significantly faster melting rate compared to the use of fin-nanoparticles combination or nano-enhanced PCM in the same volume of the triplex-tube heat exchanger.

1. Introduction

Much attention is being paid today to the development and improvement of suitable alternatives to fossil fuels because of pollution concerns and limited conventional energy resources. Solar and wind are the most attractive sources of renewable and sustainable energy. Thermal energy storage is regarded as an efficient way to go for renewable-based applications. These systems have very useful applications such as solar water heaters and building air conditioning systems [1]. Generally, storage of thermal energy can be achieved in three forms namely, sensible, latent, and thermochemical. Among these, the latent heat energy storage system (LHESS) has been found to be the most efficient, from the viewpoint of higher energy storage density [2], storing thermal energy at constant temperature [3] and operating in a large number of cycles without considerable restriction [4]. This is mainly because it stores energy during melting of the PCM giving rise to energy storage densities that are considerably higher than sensible storage. In fact, PCMs can store 5–14 times greater amounts of thermal energy compared to sensible heat storage materials for the same volume [5]. This advantage is very important, especially for applications with space constraints. However, the main downside of the LHESS is the low thermal conductivity of present-day PCMs. This weakens heat conduction in these systems leading to considerably long energy storage and retrieval times. Thus, these processes cannot be achieved in the desirable time durations. To overcome this problem, numerous investigations have been conducted to study different enhancement techniques. These include additional applications such as fins [6–10], heat pipes [11] and metal foams [12] to the PCMs to overcome the weakness of conduction heat transfer in these systems. However, it should be noted that using these techniques requires caution. They can present restrictions such as changing the flow regime, reducing the volume space for the PCM and increasing weight. Kamkari and Shokouhmand [4] reported an experimental study on the melting process and the effect of adding fins in the storage cavity containing the PCM. The study found that attaching one and three fins to the hot wall in the cavity leads to about 18% and 37% melting rate enhancement respectively. In recent years, a variety of fin shapes have been studied to enhance the performance of the fin system spreading heat into the PCM. Sciacovelli et al. [13] investigated the effect of adding

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.095
0017-9310/

Nomenclature

b	triplex-tube length [m]
C	mushy zone constant
D	diameter [m]
C_p	specific heat [J/kg K]
g	acceleration of gravity [m/s^2]
K	thermal conductivity [W/m K]
$\bar{h}$	heat transfer coefficient [W/m^2 K]
L	fin length [mm]
Nu	average Nusselt number [$Nu = \bar{h}D/K$]
Nu_0	Nu in the absence of natural convection
Γ	latent heat of Fusion [kJ/kg]
P	pressure [Pa]
S	source term
t	time [s]
T_l	liquidus temperature [K]
T_s	solidus temperature [K]
T	temperature [K]
u	velocity in r direction [m/s]
v	velocity in θ direction [m/s]
w	fin thickness [mm]
r	radial direction
HTF	heat transfer fluid
PCM	phase change material
NEPCM	nano-enhanced PCM
LHESS	latent heat energy storage system
TTHX	triplex-tube heat exchanger

Greek

β	thermal expansion coefficient [1/K]
φ	general variable
ρ	density [kg/m^3]
λ	liquid fraction
μ	dynamic viscosity [kg/ms]
ε	small parameter for avoiding division by zero
θ	tangential direction
ϕ	volume fraction

Subscripts

f	fin
m	melting
n	nanoparticles
ref	reference
Cu	copper particles
init	initial
w	wall
i,o	inner, outer tube
nb	neighboring
p	cell center
Exp	experimental
Num	numerical

tree-shaped fins to the shell-and-tube LHESS. The study was a numerical model that accounted for the thermal behavior of the system. The geometry of the tree-shaped fins with one and two bifurcations was optimized using CFD results. The results of the optimized configuration indicated about 24% enhancement.

With advancement of nanotechnology, many studies have been conducted on nanofluid flow behavior [14–17]. Consequently, nanoparticle dispersion has been proposed as a new heat transfer enhancement method for the LHESS. The nanoparticles have nominal sizes ranging from 1 to 100 nm [18–25]. Khodadadi and Hosseinizadeh [18] reported on a numerical study of the effect of adding nanoparticles to the PCM for improving the storage performance during solidification. The study stated that the increase of thermal conductivity and decrease of latent heat of fusion are the main contributors to the higher heat release rate in the nano-enhanced PCM (NEPCM) compared to the conventional PCM. Mahdi and Nsofor [26] provided a numerical simulation of triplex-tube LHESS benefiting from the combined use of nanoparticles and fins. The study investigated the effect of using these enhancement techniques in the same volume fractions of the system. Results from the study showed that significant enhancement could be achieved with these techniques. Although many studies subscribe to the advantages of nanoparticle dispersion as a heat transfer enhancement method, there are several important researches which state that the negative points of this technique outweigh its positive points. Mohamad [27] studied the fluid flow and heat transfer in the presence of nanoparticles and expressed that by considering simple physics in the investigation of nanofluid flow and heat transfer, only a slight enhancement can be observed in the heat transfer rate. In fact, adding nanoparticles to the base fluid causes several critical restrictions such as natural and forced convection suppression caused by viscosity augmentation which cannot be ignored.

The triplex-tube heat exchanger (TTHX) as a design having three concentric tubes provides a larger heat-exchange area compared to the conventional double-pipe heat exchanger. In principle, the both-sides heating approach that is applied on the annulus housing the PCM in the TTHX provides a role for higher natural convection so that faster PCM melting can be achieved. Mat et al. [28] studied the melting process of RT82 in a TTHX where three different cases including inside tube heating, outside tube heating and both-sides heating were studied. Three heat transfer enhancement methods, namely, TTHX with internal fin, with external fin, and with internal–external fin were studied. The study reported a significant improvement in the PCM melting with the use of both-sides heating approach. It was also reported that complete melting time using internal–external fin with 42 mm fin length was reduced to 43% compared to that of the TTHX without fin. It is worth mentioning here that the natural convection effect was taken into consideration in many numerical studies and neglected in some others. Studies such as [29,30] reported that in the melting process, ignoring natural convection causes large errors. According to the importance of natural convection, a considerable number of numerical and experimental researches have been conducted to investigate the behavior of different systems in the presence of natural convection heat transfer mechanisms [31–34].

Research on the acceleration of melting and solidification in the LHESS have important applications. Examples include PCM Heat Exchanger (PCMHX) used by NASA as a cooling device for satellites and spaceships for missions in low lunar orbit [35]. Acceleration of melting reduces the time of heat absorption and enhances the ability of cooling systems to reduce room temperature. Acceleration of solidification reduces the amount of time spent on transferring the absorbed heat to the ambient. Acceleration of PCM melting and solidification can be achieved through employing heat transfer enhancement techniques.

In this study, numerical simulation of the PCM melting process in a triplex-tube heat exchanger in the presence of fins was performed to study the effects of using a wide variety of fin configurations at different regions of heat exchanger. Simulations were