Energy Conversion and Management 171 (2018) 825–838

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Solidification behavior of binary eutectic phase change material in a vertical finned thermal storage system dispersed with graphene nano-plates

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ARTICLE INFO

Keywords:
Thermal energy storage
Solidification
Phase change materials
Graphene nano plates
Fins
Differential scanning calorimetry

ABSTRACT

Thermal energy storage systems (TES) find their extensive application in industrial and solar-powered thermal systems due to their high energy storage density and ability to deliver heat at isothermal conditions. But, the lower thermal conductivity of phase change materials (PCM) reduces the overall rate of heat transfer. In the present work, solidification behavior in a medium temperature (160–200 °C) finned TES with varying proportion of Graphene nano plates (GNP) is presented. The effect of anisotropy, aspect ratio, concentration, interfacial thermal resistance and non-linearity has been included to evaluate the overall thermal conductivity of GNP-PCM composite. The objective of the present study is to enhance the solidification process of a binary eutectic salt $LiNO_3$-KCl in an optimized finned TES dispersed with the different volume fraction of GNP. The detailed experimentation process starts with the preparation of binary eutectic mixture, followed by dynamic Differential scanning calorimetry analyses along with rheology testing. Empirical correlations have been developed using quadratic and cubic polynomials for viscosity and specific heat respectively. Several numerical models are analyzed to study the solidification enhancement of binary eutectic PCM using the real-time plant data of a high-temperature solar absorption chiller. Effects of Stefan and Reynolds number on the thermal performance of storage system has also been studied. Reducing the Stefan number and increasing the Reynolds number of heat transfer fluid (HTF) results in enhancing the rate of solidification process. It has been observed that natural convection currents enhances the rate of solidification and causes faster solidification in the upper annulus of TES. A reduction of 49% in the solidification time has been observed with finned TES dispersed with 5% GNP as compared to pure binary eutectic PCM.

1. Introduction

Phase change materials (PCM) are very promising option to store thermal energy and it bridges the temporal gap of irregular supply of heat. Solid-liquid phase change process at the melting temperature is responsible for storing/delivering a huge amount of latent heat as compared to sensible heat. Due to their high energy storage density and ability to deliver heat at isothermal conditions, these systems find their extensive applications in renewable and industrial processes [1,2]. Thermal energy storage systems using PCM are broadly classified as low, medium and high-temperature applications. Low-temperature TES for water heating is quite a mature technology and commercially available. Medium temperature TES (120–200 °C) is an attractive option for delivering heat to high-temperature solar absorption cooling systems, district heating networks, waste heat driven organic rankine cycles, industrial batch processes for waste heat recovery [3–5].

The low thermal conductivity of PCM's is the major challenge which drastically reduces the rate of heat transfer and restricts the charging/discharging efficiency of TES. In order to improve the thermal performance, different methods like fins, heat pipes, metal and metal oxide nano-particles dispersion, cascade systems, porous metal foams/sponge and carbon-based particles have been suggested [6–13]. Fins addition inside the PCM domain has been proven to be a low cost and effective method for thermal conductivity enhancement [14,15]. The heat can quickly be transferred using metallic fins inside the low conductive PCM due to their large surface area [16]. Abdulateef et al. [17] studied various fin geometries and found that circular and longitudinal fins gave the best thermal performance as compared to pin or plate fins. Radial fins are less costly with easy manufacturing design [18]. Khan and Khan [19] presented the discharging process of low-temperature paraffin using longitudinal fins. There is significant role of natural convection on the charging and discharging rate of a TES. But, the addition of fins restricts the natural convection currents which reduce the overall heat transfer. So, fin height and spacing should be optimized for the effective utilization of TES. It has also been proven that there is no substantial improvement in the rate of heat transfer by increasing fin

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https://doi.org/10.1016/j.enconman.2018.06.037
Received 9 April 2018; Received in revised form 14 May 2018; Accepted 11 June 2018
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Nomenclature

A_{mushy}	mushy zone parameter ($kg\,m^{-3}\,s^{-1}$)
a	aspect ratio of GNP (–)
C_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
D	diameter of pipe carrying HTF
H	enthalpy ($kJ\,kg^{-1}$)
H(a)	geometric factor depending upon aspect ratio (–)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_g	intrinsic thermal conductivity of GNP ($W\,m^{-1}\,K^{-1}$)
k_{xnp}	average thermal conductivity of GNP ($W\,m^{-1}\,K^{-1}$)
L	latent heat ($kJ\,kg^{-1}$)
M	mass (kg)
R_t	average thermal resistance between GNP & PCM ~ 10^{-8} ($m^2\,K\,W^{-1}$)
St	modified Stefan number
Re	Reynolds number
T	temperature (°C)
$\vec{v}_p$	pull velocity vector ($m\,s^{-1}$)
Z	fin height (mm)

Greek symbols

β	thermal expansion coefficient (K^{-1})
λ	liquid fraction (–)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ξ	curve fitting exponent (–)
ρ	density ($kg\,m^{-3}$)
τ	time (s)
ϕ	volume fraction of GNP

Subscripts

f	fluid
in	inlet
init	initial
l	liquid phase
liq	liquidus
npcm	GNP-PCM composite
ref	reference
on	onset
pcm	phase change material
peak	peak
s	solid phase
sol	solidus

Abbreviations

CFD	computational fluid dynamics
CNT	carbon nano tubes
DSC	differential scanning calorimetry
GNP	graphene nano plates
HTF	heat transfer fluid
PCM	phase change materials
TES	thermal energy storage systems

thickness. In our previous work [20], the optimized height of fins was obtained through the testing of several numerical models. Fin height of $Z = 0.5(R - r)$ was proven to be the best configuration at which convection currents smoothly set up with minimum material requirements.

Nowadays, there is growing interest in the use of exfoliated 2D GNP because of their low density, low cost, and high thermal conductivity as well as stability [21]. These systems can easily be scaled up to industrial level and properties are adjusted by varying the volume proportions of GNP. Khodadadi et al. [22] reviewed nanostructures for enhancing thermal conductivity in PCM and concluded that carbon-based structures outperform the other nano particles. Badenhorst [23] presented a review on the use of carbon materials for solar thermal storage applications. Raam Dheep and Sreekumar [24] also gave the same conclusion that dispersion of carbon nanostructures provide better thermal performance due to their high aspect ratio. Das et al. [25] studied the melting phenomenon of Eiconsae with GNP and found a reduction of 41% in melting time at 2% GNP. Empirical equations were used to find the effective thermal conductivity including the effect of boundary resistance. But, non-linearity effect of GNP was ignored in their analysis. Zou et al. [26] analyzed the battery thermal management using graphene, multiwall carbon nanotube (MWCNT) and a combination of both dispersed in paraffin. Addition of graphene showed improved thermal conductivity than MWCNT. Also, combined PCM with MWCNT and graphene in the ratio of 3:7 gave the highest thermal conductivity. Temirel et al. [27] investigated the solidification process of a low-temperature PCM dispersed with GNP in a spherical enclosure with convective cooling. Reduction in the overall solidification time was observed with increasing proportions of GNP. Based on the literature review, it has been observed that all heat transfer enhancement method either increases the surface area or improve the thermal conductivity of PCM. The study of combining the both are very scarce in the literature. Bazri et al. [28] reviewed PCM integrated solar collectors with fins and nano particles. It was concluded that thermal performance enhancement is dependent upon the type of PCM, particular nanoparticle used and system design. Darzi et al. [29] analyzed the melting and solidification process of a low-temperature PCM with radial fins and copper nanoparticles in horizontal annulus arrangements. It was concluded that increasing the number of fins are not beneficial during melting due to the suppression of convectional currents inside the molten PCM. Recently, Mahdi and Nsofor [30] studied the solidification phenomenon in a triplex tube using a combination of fins and alumina nano particles. It was concluded that fin-nano combination showed better heat transfer rate than dispersing nanoparticles alone. Mahdi et al. [31] studied and compared the melting process with fins and nanoparticles in a triplex tube heat exchanger. It was found that shorter fins must be placed on the upper half and longer fins to be placed on the lower half in a triplex tube system.

To the best of authors' knowledge, no study have been reported for finned thermal storage system dispersed with GNP for medium temperature applications. In our previous work, sugar alcohol d-mannitol was used in TES for double effect solar absorption chiller. But, peak solidification temperature of d-mannitol is 125 °C showing a huge super cooling which makes it unsuitable for the high temperature solar cooling system. After the careful examination of several PCM whose phase change temperature matches the medium temperature applications within the working temperature range, binary eutectic salt $LiNO_3$-KCl (50/50) has been selected. Extending our previous study, the objective of the present work is to enhance the solidification process of a binary eutectic salt $LiNO_3$-KCl in an optimized finned TES dispersed with different volume fraction of GNP. Effect of anisotropy, aspect ratio, concentration, interfacial thermal resistance and non-linearity has been included to evaluate the combined thermal conductivity of the GNP-PCM composite. Another novelty of this work is the physical preparation of binary eutectic PCM and experimental evaluation of properties like specific heat, latent heat, solidification temperature and viscosity. Empirical correlations have been developed using quadratic and cubic polynomials for viscosity and specific heat respectively. These temperature dependent properties are very significant for the accurate design of TES and serve as the input to CFD model. The detailed experimentation process starts with the preparation of binary eutectic

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