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Melting phenomenon in a finned thermal storage system with graphene nano-plates for medium temperature applications

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ABSTRACT

Thermal energy storage systems based on Phase change materials (PCM) are an attractive option to bridge the temporal and spatial gap between the energy demand and supply. But, these systems possess poor thermal conductivity causing reduced rate of heat transfer. The objective of the present study is to numerically analyze the melting process in an optimized finned latent heat storage system dispersed with varying volume fraction of Graphene nano plates (GNP). The individual effect of incorporating fins, GNP and a combination of both at different volume fraction has been studied. Effective thermal conductivity of nano-composite PCM has been theoretically evaluated including the effect of aspect ratio, interfacial thermal resistance, anisotropy, non-linear effects as well as concentration for the dispersed GNP. In this work, Dynamic differential scanning calorimetry tests are performed to evaluate the phase change temperature, latent heat and specific heat of the sugar alcohol (d- mannitol). Transient variation of liquid fraction, average temperature and radial/longitudinal temperature differentials are presented which would be useful for designing medium temperature (160–200 °C) storage systems for various applications. Fin height is varied to obtain an optimum fin size such that natural convection currents are not impeded. Various heat transfer models (including natural convection) are analysed using the actual plant data of a double effect solar absorption system at different arrangements of fins and GNP. Effect of Reynolds number and inlet temperature of HTF on the system performance have also been studied. A reduction of 68% in total melting time is observed in finned LHSS with 5% GNP as compared to a conventional system.

1. Introduction

Phase change materials are widely used to bridge the gap of discontinuous heat supply available from renewable heat sources like solar energy and intermittent industry waste heat. These materials make use of enormous latent heat instead of sensible heat for storing and delivering the thermal energy. LHSS is capable of supplying constant temperature output (depending on the melting temperature of PCM) and high energy storage density due to the utilization of latent heat. LHSS are categorized into low, medium and high temperature application systems. Low temperature system for water heating is quite a mature technology and commercially available. Medium temperature LHSS above 100 °C is an interesting option to store heat at low pressure than steam accumulators or high pressure tanks [1]. These systems also find their applications in large scale centralized high temperature solar absorption chillers, district heating grids used in large commercial establishments, hospitals and offices. Recently, solar driven organic rankine cycle and industrial thermal batch processes are being integrated with LHSS to recover low grade heat [2].

But, these materials possess low thermal conductivity which is responsible for slow melting and solidification process. Different methods like dispersion of nano particles and carbon based nano structures, using fins, metal foams, embedding heat pipes, cascade systems, encapsulation etc. have been discussed [3–9]. Addition of fins inside the PCM domain has already been proved to be an effective and comparatively cheap technique for enhancing the overall heat transfer. First reference of using fins in LHSS dates back to 1996 when Zhang et al. [10] discussed the numerical study of internally finned tube. It was concluded that increasing the height, thickness and fin numbers enhances the thermal performance of low conductive HTF. Other studies include effect of geometric fin spacing, fin materials, inner tube diameter on the overall heat transfer enhancement of LHSS [11,12]. Abdulateef et al. [13] presented a review paper in which different geometric arrangements of fins like circular, longitudinal, pin and plate fins were discussed in order to improve the thermal performance of LHSS. It was found that longitudinal and circular fins showed better thermal performance than other types of fins. Biwole et al. [14] showed the effect of fin size and spacing on the melting process in a rectangular

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Nomenclature

A_{mushy}	mushy zone parameter ($kg\,m^{-3}\,s^{-1}$)
a	aspect ratio of GNP (–)
C_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
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 $\sim 10^{-8}$ ($m^2\,K\,W^{-1}$)
r	radial coordinates (mm)
x	axial coordinates (mm)
T	temperature (°C)
$\overrightarrow{v_p}$	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

end	endset
f	fluid
in	inlet
init	initial
liq	liquidus
npcm	nano composite
o	reference
on	onset
pcm	phase change material
peak	peak
r	reference
sol	solidus

Abbreviations

CFD	computational fluid dynamics
CNT	carbon nano tubes
DSC	differential scanning calorimetery
GNP	graphene nano plates
HTF	heat transfer fluid
LHSS	latent heat storage system
PCM	phase change materials

geometry. It was concluded that thinner and longer fins increases the heat storage performance, reducing the stabilization time and temperature of the front plate, exposed to constant heat flux. Joybari et al. [15] proposed fins on a triplex tube heat exchanger and studied the effect of simultaneous charging and discharging of a low temperature PCM. Most of the previous research work has been devoted to shell and tube arrangement with fins on the PCM side in the low temperature range only. Natural convection hampers due to the addition of fins and needs geometrical optimization for their effective utilization.

Recently, carbon based structure like graphene due to its very high thermal conductivity and low density has been gaining interest in various applications. Single layer graphene has thermal conductivity of the order of 5000 $W\,m^{-1}\,K^{-1}$ [16,17]. But, synthesis of single layer graphene is difficult and expensive. So, there is a growing interest in using multilayer 2D exfoliated GNP which are having much lesser cost. These systems have the ability to be implemented at larger industrial scale and properties can be adjusted with varying proportions of nano particles. Zou et al. [18] used multi walled carbon nanotubes, graphene and a combination of both to improve the battery thermal management system. It was found that a ratio of 3:7 of carbon nano tubes and graphene in PCM increases the thermal conductivity by 124%. Mahdi and Nsofor [19] presented the solidification process of RT82 with alumina nano particles. 8% and 20% time saving was observed with 3–8% loading of alumina particles. In their recent publication [20], the solidification of a low temperature PCM in a triplex tube using fins and metal nano particles was presented. Raam Dheep and Sreekumar [21] presented a comprehensive review of the nanomaterial's influence on the PCM properties for solar thermal applications. It was reported that carbon nanostructures with more aspect ratio outperforms the metal nanoparticles. Das et al. [22] investigated the melting phenomenon in a low temperature PCM with GNP in a vertical shell and tube arrangement. It was found that total melting time was reduced by 41% with 2 vol% graphene at a water inlet temperature of 60 °C. Eicosane was used as PCM and all the properties were taken directly from the literature. Effective thermal conductivity was obtained by considering the role of boundary resistance and ignoring the non-linear effects of GNP.

Kant et al. [23] studied the impact of varying proportions of GNP in an aluminum square cavity filled with three low temperature PCM. It was found that nanoparticles enhances the thermal conductivity but restricts the convection heat transfer for large cavities. Maxwell relation was used to obtain effective thermal conductivity of nano-composite. Babaei et al. [24] discussed the effect of graphene and CNT incorporation in n-octadecane. The graphene inclusions showed better thermal performance as compared to CNT. Many empirical correlations were given to evaluate the effective thermal conductivity of graphene-PCM composite which were input to CFD models. These correlations were improved by considering various factors like interfacial thermal resistance, anisotropy and aspect ratio. It is also an established fact that increase in effective thermal conductivity with increasing proportion of GNP of nano composite is nonlinear. This non-linear behavior is a result of interaction amongst GNP along with their high aspect ratio and thermal conductivity [25]. In this work, effective thermal conductivity of nano-composite PCM has been theoretically evaluated including the effect of aspect ratio, interfacial thermal resistance, anisotropy, non-linearity as well as concentration for the randomly dispersed GNP.

To the best of the knowledge of authors, no studies have been reported so far for finned LHSS with GNP for medium temperature applications (160–200 °C). The objective of the present study is to numerically analyze the melting process in an optimized finned latent heat storage system dispersed with varying proportion of GNP. Different cases of LHSS with only fins, LHSS with only GNP and a combination of both have been compared and discussed. Optimum fin height for maximum thermal performance is evaluated and combined finned system with GNP has been reported to get better insight of melting process. In this work, Dynamic DSC tests are performed to evaluate PCM properties. Numerical model has been developed using actual experimental data of a double effect solar cooling plant.

2. DSC characterization and results

Due to lack of clear standards for PCM characterization, there is always a mismatch between the actual PCM properties (especially