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Effect of carbon nano inclusion dimensionality on the melting of phase change nanocomposites in vertical shell-tube thermal energy storage unit

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ABSTRACT

In the present work, we numerically investigate the melting phenomena of carbon based nanocomposites in vertically oriented shell-tube latent heat thermal energy storage system. Organic alkane *n*-eicosane was considered as the phase change material and carbon allotropes as the nano fillers to enhance the thermal conductivity of *n*-alkane. The effect of different carbon allotropes like nanodiamond (spherical), single-walled carbon nanotubes (one-dimensional) and graphene nanoplatelets (two-dimensional) were considered. Thermal conductivity of nanocomposites was modeled using effective medium based formulation taking the interfacial thermal boundary resistance between nanomaterial and the surrounding host matrix into account. Numerical results show that spherical nano inclusions do not enhance the melting rate due to limited enhancement in the thermal conductivity of nanocomposites. However, the inclusion of one-dimensional and two-dimensional nanostructures shorten the melting time by ~15% and ~25% respectively at 1 vol% loading as a result of higher thermal conductivity enhancement.

1. Introduction

Solar energy is one of the most promising sources of renewable energy resources. Due to the intermittent nature of sunlight, storage of excess thermal energy is of vital importance to match the energy demand and supply. Thermal energy storage (TES) system is popular one among the various storage systems. Generally, TES is classified into two types - latent heat thermal energy storage (LHTES) and sensible heat thermal energy storage (SHTES). Higher storage density as well as isothermal nature during phase transition make LHTES more suitable than SHTES. On the other hand, lower thermal conductivity of phase change materials (PCM) is a concern which limit the energy storage and discharge rates. Therefore, higher thermal conductive PCM are necessary for the advancement of the LHTES systems.

Vyshak and Jilani [1] numerically investigated the melting behavior of PCM in cylindrical, rectangular and cylindrical shell-tube configuration for a constant PCM volume and heat transfer surface area. It was shown that cylindrical shell-tube configuration showed better performance among these configurations. Esen et al. [2] proposed two different cylindrical shell-tube configurations and calculated the melting behavior of these systems numerically. In their calculations, PCM was placed on the shell side and the heat transfer fluid (HTF) was allowed to flow inside the tube and vice versa. It was reported that the placing of PCM in the shell side resulted in less melting time compared to the other configuration. Ettouney et al. [3] suggested importance of HTF flow direction experimentally in vertical shell tube heat storage system. It was found that upward flow of HTF intensified the natural convection inside the PCM. Further impact of different operational parameters like mass flow rate of HTF, inlet HTF temperature on thermal performance of shell-tube heat storage system was performed experimentally and numerically by several authors [4–6]. Several researchers have performed numerical and experimental results to optimize the geometrical configuration of the TES system and understand the effect of operational parameters. However, the thermal conductivity of PCM used to store and release energy is in the order of 0.2–0.5 W m^{-1} K^{-1} which results in the reduced heat transfer performance of LHTES systems.

The commonly adopted techniques to enhance the thermal conductivity of PCM is to include a high thermal conductive material in the PCM matrix [7–9] and incorporation of fins on the heat exchanger wall [10–13]. Mettawee and Assassa [14] investigated

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Nomenclature

a_s	aspect ratio
A_{mushy}	Mushy zone constant (kg/m^3 s)
R_{Bd}	thermal boundary resistance (m^2 K/W)
T_{htf}	inlet temperature of HTF (K)
T_i	initial temperature of PCM (K)
T_m	melting temperature of PCM (K)
c_p	specific heat (J/kg K)
$\vec{g}$	gravity acceleration (m/s^2)
m_{inlet}	inlet mass flow rate of HTF (kg/min)
A	intrinsic viscosity (kg/m s)
H	total enthalpy (J/kg)
K	thermal conductivity (W/m K)
L	latent heat (J/kg)
P	pressure (N/m^2)
T	temperature (°C)
V	velocity (m/s)
q	heat flux (W/m^2)

Greek letters

ΔT	$(T_{htf} - T_i)$
$\in$	numerical constant
Δ	liquid fraction
α	thermal expansion coefficient (1/K)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
φ	particle volume fraction

Subscript

htf	heat transfer fluid
eff	effective
liquidus	liquid phase of PCM
max	maximum packing factor
p	dispersed phase
pcm	phase change material
ref	reference
solidus	solid phase of PCM

the thermal performance of LHTES system with aluminum powder based PCM. Due to increment of thermal conductivity of PCM, 60% melting time reduction was achieved. Xiao and Zhang [15] experimentally investigated the melting behavior of expanded graphite/paraffin composites and reported a 68% reduction in melting time. Carbon based allotropes possess exceptionally high thermal conductivity compared to other metallic and meatal oxide based nanoparticles. Especially, recent experimental measurements of thermal conductivity of carbon nanotubes and graphene show excellent thermal conductivity in the range of 3000–5000 W m^{-1} K^{-1} [16,17]. Hence, it is natural to anticipate that the development of nano composites with carbon additives will yield promising enhancement at limited loading compared to other structures. Recent experiments on nanoparticle based suspensions show that the thermal conductivity enhancement is significantly limited and can be predicted using effective medium theory. Carbon nanotubes and graphene show significantly higher thermal conductivity enhancement compared to nanoparticles due to their large aspect ratio and higher thermal conductivity. However, despite the high intrinsic thermal conductivity of carbon nanostructures, the effective thermal conductivity enhancement is limited due to the presence of high interfacial thermal resistance between nano structure and the surrounding PCM matrix [18–21].

Sciacovelli et al. [22] numerically investigated the influence of copper nanoparticles in vertically oriented shell-tube LHTES system. They showed a 15% reduction in melting time compared to that of pure paraffin at 4 vol% loading of copper nanoparticles. However, in their numerical calculations the interfacial thermal resistance between the nanoparticle and the surrounding PCM was not taken into account while calculating the effective thermal conductivity using Maxwell's model. Das et al. [23] numerically investigated the effect of heat transfer fluid temperature and the graphene concentration on the melting characteristics of *n*-eicosane based nanocomposites in shell-tube LHTES systems. It was shown that the melting time decreases with increasing the loading of graphene nanoplatelets and also increasing temperature of heat transfer fluid. In their numerical calculations, effective thermal conductivity of nanocomposites was calculated using effective medium theory considering the role of interfacial thermal resistance and effective viscosity was estimated using the Kreiger - Dougherty approach.

In this work, we systematically investigate the effect of carbon nanomaterial dimensionality on the melting characteristics of PCM in LHTES systems. To enhance the thermal conductivity of PCM, high conductive carbon nanomaterials of different dimensionality namely nano-diamond (spherical), single-walled carbon nanotubes (SWCNT, 1-dimensional) and graphene nanoplatelets (GnP, 2-dimensional) are considered. For a constant HTF temperature and constant loading of the nanomaterial, we show that the inclusion of 1 vol% GnP and 1 vol% SWCNT show ~25% and ~15% reduction in melting time compared to that of pure PCM. On the other hand, inclusion of nano-diamond do not show any appreciable decrease in the melting time due to limited enhancement in the thermal conductivity.

2. Modeling

2.1. System description

For the numerical calculations, we have made use of a vertically oriented cylindrical single shell-tube LHTES system which is used by Akgun et al. [5] for their experiments. Fig. 1 shows the 3 dimensional schematic of the computational model which is created based on the dimensions reported in the Ref. [5]. Shell and tube is situated concentrically in the system. Water is used as HTF. HTF flows through the inner tube of the system at constant temperature. PCM is placed in annular gap between tube wall and shell wall. Shell wall and tube wall are considered as steel and high conductive copper material. For melting purpose, initially, PCM is at ambient temperature (T_i) in solid phase. Hot inlet HTF flows inside the tube at constant temperature (T_{htf}) that is higher than PCM melting temperature $(T_{htf} > T_m)$. The melting process is continued until solid phase of PCM transforms into liquid phase, thus latent heat stores into PCM.

2.2. Governing equations

In this section, we show the governing equations and the mathematical formulations adopted to model the melting characteristics of the nanocomposites. The governing equation are shown below: