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Research Paper

Melting of graphene based phase change nanocomposites in vertical latent heat thermal energy storage unit

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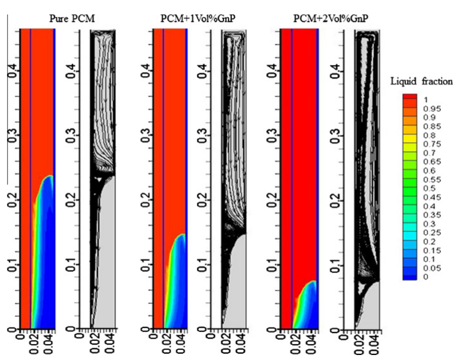
HIGHLIGHTS

- Melting of graphene based phase change nano composites is investigated numerically.
- Melting time decreases with increasing heat transfer fluid temperature.
- Melting time decreases with increasing graphene loading.
- At 343 K fluid temperature, 2 vol% graphene decreases the melting time by 37%.

GRAPHICAL ABSTRACT



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ABSTRACT

The present study deals with the investigation of melting phenomena in single vertical shell-and-tube latent heat thermal energy storage unit. A two dimensional axi-symmetric computational fluid dynamics model based on the enthalpy-porosity method was developed to investigate the melting behaviour. Organic alkane *n*-eicosane and *n*-eicosane/graphene nanosheets with different volume fractions were considered as the phase change materials (PCMs). Water was considered as the heat transfer fluid (HTF) flowing inside the tube and the PCM is filled in the shell side of thermal energy storage unit. A variety of numerical simulations were performed for different heat transfer fluid inlet temperatures and varying loadings of graphene nanosheets. Numerical calculations show that higher inlet temperature of the heat transfer fluid decreases the melting time due to accelerated natural convection. We also show that the inclusion of graphene nanosheets significantly decreases the melting time due to the enhanced thermal conductivity of PCM. At 2 vol% graphene laoding, melting time reduces significantly by ~41% when the HTF temperature is 60 °C and ~37% when the HTF temperature is 70 °C.

1. Introduction

Thermal energy storage (TES) system is a key part in research and industry application that helps to mitigate existing gap between energy supply and demand considering past scenarios and ongoing situation. It can be seen that increment in level of green-house gases emission as well as climb in fuel crisis create a major issue in environment and daily life. Such problems compel to think about other sources of energy and recovery of waste energy. Solar energy is an intermittent energy source and its intensity depends on weather, location, time. That drives researchers to

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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)
g	gravity acceleration (m/s^2)
m_{inlet}	inlet mass flow rate of HTF (kg/min)
A	intrinsic viscosity (kg/m s)
D	diameter of HTF tube
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
$\mathcal{B}$	liquid fraction
α	thermal diffusivity (m^2/s)
α	thermal expansion coefficient (1/K)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
φ	particle volume fraction

Subscripts

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

conceive of TES system. Latent heat thermal energy storage (LHTES) and sensible heat thermal energy storage (SHTES) are two type of TES system. Due to the higher energy storage density and isothermal nature during phase transition, latent heat thermal energy storage (LHTES) is more heedful than sensible heat thermal energy storage (SHTES).

Exercise of LHTES system gives a new direction for energy storage application and various geometrical configurations have been proposed for phase change material (PCM) based energy storage systems. Zivkovic et al. [1] numerically compared the performance of rectangular and cylindrical configurations and reported that rectangular configuration took half the melting time with respect to cylinder configuration. Vyshak et al. [2] numerically conducted a comparative study on melting time for three PCM encapsulated different configurations like cylinder, rectangular, cylindrical shell-tube with equal mass of PCM and surface area of heat transfer. It was concluded that cylindrical shell-tube configuration took least time for melting. The effect of geometrical configuration was more visible with increasing of the PCM mass. Esen et al. [3] described two different shell-tube geometrical configurations: HTF was flowed parallel to tube on shell side and PCM was placed in inside of tube, another one was vice versa of first one respectively. The consequence of the study was that due to thicker PCM mass, first configuration took more time for melting. From above literatures, it is concluded that most desirable LHTES system is shell-tube energy storage system with inner tube HTF flow.

Sari et al. [4] investigated performance of vertical shell-tube based thermal energy storage system experimentally. Author pointed out the solid-liquid interface movement, natural convection phenomena in liquid PCM. Ettouney et al. [5] conducted experiments for vertical double pipes configuration, it was concluded that natural convection in PCM strongly depends on direction of HTF flow, natural convection in liquid PCM was dominated for upward HTF flow, natural convection effect is limited for downward HTF flow. Akgun et al. [6] performed experimental study on melting and solidification in vertical shell-tube storage system. The effect of operational parameters i.e. inlet HTF temperature, mass flow rate of HTF for melting and solidification performance was investigated. Adine et al. [7] numerically studied the thermal behaviour of shell-tube heat storage unit using PCMs numerically and analyzed effect of inlet HTF temperature, mass flow rate of HTF on thermal performance of LHTES system.

Different configurations and operational parameters have been studied but low thermal conductivity of PCM remain a great challenge. Lower thermal conductivity of PCM limits the melting and solidification rate of PCM which still remain a concern for practical applications of this system. To enhance the melting and solidification rates researchers have adopted techniques like utilization of fins [8–12], multitube configurations [13], multiple PCMs with different melting temperatures [7], PCM-expanded graphite composites with high thermal conductivity [14,15] and metal or graphite foam structures [16–18].

Few researchers investigated the effect of inclusion of high thermal conductive nanoparticles in the PCM to enhance the thermal conductivity. In this context, various metals and metallic oxide nanoparticles, carbon based nanofillers were used for this purpose [19,20]. Recently, it was demonstrated that graphene nanosheets a two dimensional allotrope of carbon enhances the thermal conductivity of organic PCMs significantly [21–24]. Mettawee et al. [25] experimentally investigated thermal performance of LHTES with aluminum powder added PCM. It was shown that melting time reduced by 60%. Sciacovelli et al. [26] numerically calculated the effect of CuO nanoparticles in thermal energy storage unit. Melting time was reduced by 15% at 4 vol% loading of nanoparticles in PCM. Xiao et al. [27] experimentally investigated the heat transfer characteristics of paraffin/expanded graphite composites and compared the results with numerical calculations.

It can be seen from the literature that majority of the research work on LHTES systems used pure PCMs. The energy storage and retrieval rate of such systems were limited due to the poor thermal conductivity of the PCMs. Experimental and numerical investigations on the effect of nanomaterial inclusions were limited. To enhance the thermal conductivity of such PCMs, graphene nanoplatelets (GnP) were used as nano inclusions in this work. The effective thermal conductivity of nanocomposites was predicted based on the effective medium model calculations considering the role of interfacial thermal resistance between the graphene sheets and the surrounding PCM. We numerically calculate the thermal performance of vertical shell-tube latent heat thermal energy storage system with pure PCM *n*-eicosane and compare its performance with graphene based nanocomposites at different inlet HTF temperature conditions. We demonstrate that the inclusion of graphene significantly improves the performance of the thermal storage systems.