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Heat transfer study of phase change materials with graphene nano particle for thermal energy storage

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ABSTRACT

The thermal conductivity of commonly used phase change materials (PCM) for thermal energy storage (TES), such as, fatty acids, paraffin etc., is relatively poor, which is one of the main drawbacks for limiting their utility. In the recent past, few attempts have been made to enhance the thermal conductivity of PCM by mixing different additives in the appropriate amount. Graphene nanoparticles, having higher thermal conductivity may be a potential candidate for the same, when mixed appropriately with different PCM. In present study authors have carried out the numerical investigation for the melting of graphene nanoparticles dispersed PCM filled in an aluminum square cavity heated from one side. In this work, the graphene nanoparticles are mixed in three different volumetric ratios (1%, 3%, and 5%), with three different commonly used categories of organic, inorganic and paraffin PCM (namely, Capric Acid, $CaCl_2 \cdot 6H_2O$, and *n*-octadecane) to see the effect on melting of composite PCM developed. The resulting transient isotherms, velocity fields, and melting front and melt fractions thus have been deliberated in detail. These results clearly indicate that the addition of graphene nanoparticles increases melting rate but can also hamper the convection heat transfer within large cavities. The study also shows that such enhanced PCM can be effectively used for different TES applications in different fields. The prediction of temperature variation and rate of melting or solidification may be found useful especially for designing such TES devices.

1. Introduction

The growth of the civilization in general and global economic growth, in particular, has largely depended on human efforts to efficiently produce, store and convert to a new form. This is deeply motivating research area and requires development efforts from several spheres of engineering, science and technology, and especially from material sciences. TES related research is mainly concentrated towards efficient use of thermal energy, generally, the solar energy but has considerable interest for thermal energy managing in industries too. One of the main concerns in thermal energy management is to practice materials having high energy storage capacity with high reliability and less aging effect. In the recent past there has been huge amount of research efforts devoted to developing such novel materials for variety of applications, such as buildings, textiles, and space heating. These materials are commonly known as PCM, are promising thermal storage materials for storing and discharging bulk amounts of latent heat throughout phase change process (Fang et al., 2009; Hasnain, 1998; Kant et al., 2016a; Murat Kenisarin and Mahkamov, 2006) with regulated time intervals associated as per energy demand. Though, the criteria for the choice of PCM for a specific application is its melting temperature, but other properties such as the latent heat of fusion, thermal conductivity, thermal stability, density and lower volume change, also play significant role in better designing of a product and therefore these are essential to be considered (Ling and Poon, 2013; Mehling and Cabeza, 2007). Hence, the optimization of material properties as per requirement is quite challenging and novel materials with better efficiency are being continuously explored with time. Additionally, most applications of PCM require high thermal conductivity, though numbers of PCM usually employed lack the same. The lower thermal conductivity of PCM leads to the increase of heat transfer time for the storage materials causing the poor TES system performance. To increase the rate of heat transfer, several experimental and numerical studies have been performed, for enhancing thermal conductivity using metal matrix, metallic fins, thermal conductive

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Nomenclature

C_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
Cp_g	specific heat of graphene nano-particles ($J \cdot kg^{-1} \cdot K^{-1}$)
d_p	diameter of nano-particles (m)
g	gravitational acceleration constant ($m \cdot s^{-2}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
H	height of cavity (m)
k_g	thermal conductivity of graphene nano-particles ($W \cdot m^{-1} \cdot K^{-1}$)
L_f	latent heat of Fusion ($J \cdot kg^{-1}$)
q_w	heat flux ($W \cdot m^{-2}$)
P	pressure (Pa)
T	temperature (K)
t	time (s)
u	velocity ($m \cdot s^{-1}$)
v	velocity in y direction ($m \cdot s^{-1}$)
W	width of aluminum cavity (m)
x	distance in x direction (m)
y	distance in y direction (m)
ρ	density ($kg \cdot m^{-3}$)
Φ	volume fraction of nano-particles
Φ_w	weight fraction of nano-particles
ΔT	transition temperature (K)
μ	dynamic viscosity of melted PCM (Pa·s)
β	thermal expansion coefficient of PCM

Subscripts

PCM	phase change materials
NPCM	nanoparticle dispersed PCM
Solid	PCM in solid state
Liquid	PCM in liquid state

foams, containers with a honeycomb structure, encapsulation, and the emulsification of highly thermal conductive nanoparticles, etc. (Kibria et al., 2015; Liu et al., 2015; Nurten et al., 2015; Mills et al., 2006). Review by Khodadadi et al. (2013), excellently covers numerous aspects of many of these efforts made in recent past to enhance the thermal conductivity of PCM. These studies indicate that the appropriate mixing of nanoparticles and encapsulation, when done together, could be crucial in significantly augmenting the thermal conductivity of the PCM. Few studies have appeared in the recent past on the solidification and melting pure (Kant et al., 2016b) and of nano-enhanced PCM. The nanoparticle-dispersed PCM to qualitatively upgrade TES technology could be highly beneficial for many applications, for instance, efficient storage of solar energy (Shukla et al., 2017a, 2017b), thermal regulation of photovoltaic (Kant et al., 2016c; Hasan et al., 2015), TES in buildings by applying at one side of container to building envelope, cooling of engines, etc. (Hunger et al., 2009; Jradi et al., 2013; Karthikeyan et al., 2014; Salunkhe and Shembekar, 2012; Shi et al., 2014). Khodadadi and Hosseinizadeh (2007) carried out a numerical simulation of water as PCM with copper (Cu) nanoparticles using FLUENT software and reported that the accumulation of Cu nanoparticle in water results in the augmentation of thermal conductivity and consequently affects the melt fraction as well. Arasu and Mujumdar (2012) carried out a numerical study using the enthalpy-porosity formulation of Al_2O_3 nanoparticle suspended PCM with different weight ratio in a square container which was heated from the bottom and vertical side while the opposite wall was maintained at constant temperature. The study described that the liquid-solid interface shape and fluid flow mainly subjected to the thickness of the liquid layer, during the advancement of melting. The rate of melting decreases with the increase in the volumetric composition of alumina (Al_2O_3) for both ways. Sebti et al. (2013) conducted a comprehensive numerical investigation to examine heat transfer augmentation in the melting process in the square cavity through dispersion of Cu nanoparticles. Dispersed nanoparticles in PCM caused an upsurge in thermal conductivity compared to conventional PCM, which leads to heat transfer improvement and a higher melting rate. In addition, heat transfer rate in the nanofluid increased and the melting time reduced as the volume concentration of nanoparticles increased. Dhaidan et al. (2013b) carried out an experimental and numerical study on CuO nanoparticle suspended PCM within a circular container having a constant heat flux on the surface of the container, including the effect of eccentricity. Dhaidan et al. (2013a) carried out similar research as Dhaidan et al. (2013b)for the square cavity. Melting of alumina (Al_2O_3) dispersed PCM in a cavity with two different arrangements of heat sources–sink pairs flush-mounted on the upright sidewalls, was investigated numerically by Ebrahimi and Dadvand (2015). The impacts of the nanoparticle mixing were analyzed. In all studied cases, the volume fraction of Al_2O_3 nanoparticles of 2% resulted in the maximum melting rate. These studies indicate the importance of different approaches to upsurge thermal conductivity for efficient utilization of heat energy storage capacity of PCM. Alshaer et al. (2015) carried out a numerical study to see the effect of insertion of RT-65 and Nano carbon tubes in carbon foam matrices of dissimilar porosities. Tasnim et al. (2015) reported thermal performance of porous latent heat TES system filled with nanophase change material. The outcomes obtained from scale analysis in simplified relationships among different dimensionless parameters. These studies also suggest the importance of adding nanoparticles to upsurge the thermal conductivity of PCM which further enhances heat transfer rate in the storage materials.

Most of the research studies performed so far focussed on investigating the moving boundary problem for a specific geometry and boundary conditions. Studies related to the melt fraction for a PCM storage system with the different volume fraction of nanoparticles are lacking, though these play a significant role in designing a TES. This is the main motivation of the current work. Moreover, graphene has been found to be very high thermal conductive which could be potentially used for enhancing the thermal conductivity of PCM. In the present study, authors have explored the effect of mixing graphene nanoparticles as an additive in different PCM with varying volume fractions of nanoparticles, when kept in an aluminum container. The three different PCM considered for the present study i.e. Capric Acid, $CaCl_2 \cdot 6H_2O$ and *n*-octadecane (Organic, Inorganic, and Paraffin) which are commonly used for different TES applications, i.e. building application (by applying one side of container at building envelope) (Sharma et al., 2013), solar photovoltaic thermal regulation (Kant et al., 2016b), solar drying application (Kant et al., 2016d) and solar greenhouse application (Shukla et al., 2016), etc.

2. Computational model and boundary condition

The dimensions and geometry of computational model for the present study are shown in Fig. 1. The nanoparticle dispersed PCM (NPCM) is filled in the enclosure of size 25 mm × 25 mm