



Experimental and numerical investigation on the performance of carbon-based nanoenhanced phase change materials for thermal management applications



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ARTICLE INFO

Keywords:

Phase change material
Paraffin wax
Carbon-based nanoparticles
Thermal management

ABSTRACT

Phase change material (PCM)-based thermal management is one of the most promising approaches for the thermal management of energy conversion devices such as electric vehicle batteries and photovoltaic cells. However, most of the PCM present inherently low thermal conductivities, which result in deficient temperature control capacity in these applications. Several types of carbon-based nanoparticle have been explored to enhance the thermal conductivity of pure PCM. Despite the significant improvements in their thermal conductivity, the heat transfer in the liquid phase nano-enhanced PCM is expected to decrease due to the presence of the nanoparticles matrices. In this study, three types of carbon-based nanostructures are embedded in a paraffin to investigate their heat transfer performance for thermal management applications. The experimental results indicate that the addition of nanoadditives can improve the heat conduction of solid phase paraffin with slight latent heat degradation. But it also drastically increases the dynamic viscosity of composites which suppresses the natural convection heat transfer in the melted PCM. The thermal behavior of nanocomposites during the melting process is experimentally and numerically examined. Results reveal that adding carbon nanofibers and graphene platelets deteriorate the thermal performance of the pure paraffin. However, an enhanced thermal response observed when graphite-based nanocomposites at 7.5 and 10 wt% are used due to their 620% and 1100% solid phase thermal conductivity enhancement, respectively. The results of the current work suggest that there is a trade-off between the thermal conductivity enhancement and natural convection suppression of nanocomposites that can be used in the optimal design of PCM-based thermal management systems.

1. Introduction

Paraffin-based phase change materials (PCM) are considered as a promising energy storage medium through solid–liquid phase change at the melting point temperature. This energy storage could have significant applications in the solar energy storage [1–3] and passive cooling of portable electronics [4–6]. However, the performance of paraffin-based PCM is restricted by their low thermal conductivity. The amount of phase change during a heating or cooling process depends on the effective thermal penetration into the PCM. Also, in the thermal management of temperature sensitive electric devices (e.g. passive cooling of lithium-ion batteries), it is crucial to control the contact temperature between the PCM and the device. The amount of heat penetration and the contact temperature of two bodies in thermal contact are functions of the PCM thermal conductivity. Thus, it is essential to enhance the thermal conductivity of PCM for increasing the

amount of thermal energy storage or to control the contact temperature.

A number of methods were reported to enhance the effective thermal conductivity of paraffin-based PCM [7–10]. The addition of highly conductive carbon-based nanoparticles was proposed as an effective approach to increase the thermal conductivity of PCM due to their low densities and intrinsic high thermal conductivities within the range of 1000–6000 W/m K. Table 1 shows a summary of some recent works on the thermal conductivity enhancement of PCM utilizing different types of nano-sized carbon fillers. It is observed that there is a considerable discrepancy between the thermal conductivity enhancement results, which may be due to the differences in the thermal properties of matrix material and/or preparation methods.

In contrast to the intensive research on thermophysical properties of nano-enhanced PCM (NePCM), less work presented on the phase change heat transfer characteristics of these materials in cylindrical

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Nomenclature		T_{∞}	ambient temperature (K)
C_p	specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)	\mathbf{u}	velocity vector (m s^{-1})
\mathbf{g}	gravity acceleration vector (m s^{-2})	<i>Greek letters</i>	
h	convection heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	μ	dynamic viscosity (Pa s)
H	container height (m)	ρ	density (kg m^{-3})
\mathbf{I}	identity matrix	ϕ	mass fraction
k	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	<i>Subscripts and superscripts</i>	
L	latent heat (J kg^{-1})	<i>ini</i>	initial
\mathbf{n}	normal vector	<i>max</i>	maximum
p	static pressure (Pa)	<i>np</i>	nanoparticle
q''	heat flux (W m^{-2})	T	transpose
R	container radius (m)		
t	time (s)		
T	temperature (K)		

geometry. The heat transfer characteristics by treating the NePCM as homogeneous materials with equivalent thermophysical properties were numerically studied in both solid and liquid phases. The solid phase heat transfer was conduction-dominated and the observed enhancement in heat diffusion was attributed to the increased thermal conductivity of NePCM, which was verified by experiments [11–13].

However, the presence of nanoparticles may negatively affect the heat transfer in the liquid phase, because the natural convection in a melted PCM usually dominates. A summary of the recent studies focusing on the phase change heat transfer of NePCM in different geometries is provided in Table 2. Numerical studies show an acceleration of melting in NePCM in cylindrical vessel compared to the pure phase change material due to the higher thermal conductivity of NePCM in solid and liquid phases [14–17]. However, some of these numerical results are questionable due to the considerable uncertainties associated with the thermal conductivity and viscosity data used for the NePCM. The experimental measurements indicate that the thermal conductivity of the liquid phase PCM increases slightly even when fully percolating concentrations are used. Thus, both solid phase and liquid phase properties are significantly important for the accurate modeling of melting of NPCM. Using a single thermal conductivity equation, as commonly utilized in the literature, may not result in sufficiently precise predictions. The presence of the nanoparticles also increases the viscosity of the melted PCM and leads to the degradation of natural convection. For instance, measurements done by Fan [18] showed that

the thermal conductivity of the NePCM was enhanced by 50% at 1 wt% concentration, while the undesirable dynamic viscosity was increased more than 60 times for the same nanoparticle concentration.

Although this dramatic growth in viscosity highly deteriorates the natural convection, higher nano-filler concentration NePCM are of interest due to their so-called form-stability. However, there is no data on the heat transfer characteristics of form-stable NePCM available in the literature. Such a data is valuable in the design of electric devices passive thermal management systems where the form-stability is favorable in order to minimize the risk of melted PCM leakage.

The purpose of this work is to assess and compare the thermo-physical properties, and the heat transfer enhancement of the phase change nanocomposites using different carbon additives. In this paper, three paraffin based nanocomposites are prepared by using different carbon additives, namely, carbon nano-fiber (CNF), graphene nanoplatelets (GNP), and graphite nano-powder (GrP). The temperature dependent thermophysical properties of these nanocomposites are first measured and analyzed by a scanning electron microscopy (SEM) and a differential scanning calorimeter (DSC). The thermal conductivity of the samples is measured by a C-therm thermal analyzer. The thermal responses of the NePCM composites during the phase change are investigated both experimentally and numerically.

2. Preparation of nanocomposites

A paraffin wax with a nominal melting point (T_m) of 333.15 K is adopted as the base PCM. The carbon-based nanoparticles are purchased from MK Impex Corp., Ontario, Canada. The materials are used as received without further purification in all experiments. The preparation process of phase change composites made of nanoparticles and organic PCM was previously reported in the literature [19], and a similar method is used in this work to manufacture the CNF-, GNP- and Graphite-based nanocomposites. The nanoparticles at desired weights are added to the melted PCM at 90 °C and intensively stirred for 30 min to provide a homogeneous mixture. A temperature higher than the PCM melting point is preferred as a relatively low viscosity of the molten PCM facilitates the dispersion of the nanoparticles. A very small amount of PolyVinylPyrrolidone-40 (Sigma-Aldrich, Oakville, Canada) is added to the mixture as a dispersing additive to assure a good dispersion of the nanoparticles in the liquid PCM. Finally, the liquid composite is rigorously sonicated at about 90 °C for 2 h prior to the solvent evaporation. For each nanoparticle, four samples with different weight fractions of carbon additive (2.5%, 5%, 7.5% and 10%) are prepared. The stability of each nanocomposite is assessed to make sure that during the melting/solidification cycles, the samples will remain homogeneous. A series of repeated thermal cycles are performed using an electric hot plate with a temperature controller. After each cycle, visual observation is used to assure the nanocomposite's homogeneity. The thermophysical

Table 1
Studies on the thermal conductivity enhancement of carbon-based NePCM.

Nanoparticle type(s)	Nanoparticle thickness/diameter (nm)	Max. Concentration, %	Max. Thermal Conductivity Enhancement ($k_{\text{NePCM}}/k_{\text{PCM}}$), %	Reference
CNF	9000	10 wt	507.8	[25]
CNF + indium	10,000	21 vol	4100	[30]
SWCNT	30	2 wt	180	[31]
Graphene	2	0.3 wt	1100	[32]
Graphene	15	20 vol	2800	[33]
MWCNT	65		832	
CNF	200	10 wt	145	[26]
CNT	30		124	
S-MWCNT	815	5 wt	131	[27]
L-MWCNT	3050		123	
CNF	150–200		115	
GNP	420		273	
MWCNT	–	5 wt	200	[10]
Graphene	–		1	
Graphite	–		1292	
GNP	1000/10	5 vol	204	[34]
	15,000/10	4 vol	966	

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