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Phase-change heat transfer in a cavity heated from below: The effect of utilizing single or hybrid nanoparticles as additives

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ABSTRACT

The present study deals with the effects of hybrid nanoparticles on the melting process of a nano-enhanced phase-change material (NEPCM) inside an enclosure. The bottom side of the cavity is isothermal at a hot temperature while the top wall is isothermal at a cold temperature and the left and right walls are insulated. The governing partial differential equations are first non-dimensional form and then solved using the Galerkin finite element method. Some of the dimensionless parameters are kept constant such as the Prandtl number, the Rayleigh number, the Stefan number and the ratio between the thermal diffusivity of the solid and liquid phases while the volume fraction of nanoparticles, the conductivity and viscosity parameters, and the Fourier number are altered. It is found out that increasing the values of the nanoparticles volume fraction, viscosity and conductivity parameters leads to significant variations in the solid-liquid interface for large values of Fourier number. Moreover, increasing the conductivity parameter and decreasing the viscosity parameter at the same time can cause an augmentation in the liquid fraction.

1. Introduction

Latent heat thermal energy storage is an effective and reliable way of storing energy compared to the other ways of energy storage including thermochemical reactions. Thus, phase-change processes such as melting can play a vital role in today's need for energy storage. A small volume of Phase Change Materials (PCM) can store a significant amount of energy during a solid to liquid phase-change process. Nowadays, PCM are extensively utilized in a variety of application such as solar heating systems [2,38], cooling the electronic devices [15,26], finned heat pipe-assisted thermal energy storage systems [44,45] and waste heat recovery [31,32,35]. Unfortunately, PCM employed in energy storage units have low thermal conductivity which reduce the heat absorption rate. Several methods are proposed to increase the thermal performance of the storage units, among them, using nanoparticles can enhance the thermal conductivity of a PCM even for a small volume fraction of nanoparticles.

A comprehensive study has been done regarding the effects of nanoparticles on the enhancement of the thermophysical and heat transfer potential of the conventional fluids. Rashidi et al. [36] have studied the thermal behavior of Al_2O_3–water and γ Al_2O_3–$C_2H_6O_2$ nanofluids in boundary layer over a vertical stretching sheet. They reported that both of the dynamic viscosity and thermal conductivity of the investigated nanofluids can significantly affect the thermal behavior of nanofluids. Ismael et al. [19] and Chamkha et al. [7] addressed the natural convective heat transfer of copper-water nanofluids in cavities. They concluded that the presence of nanoparticles could enhance the heat transfer; however, the heat transfer enhancement of nanofluids is under the significant influence of the flow conditions. Makulati et al. [29] have addressed the natural convective heat transfer of Al_2O_3-water nanofluids in a C shape cavity. They studied the effect of nanoparticles volume fraction on the natural convective heat transfer and found that in some cases the presence of nanoparticles could decrease the heat transfer in the cavity. Sheremet et al. [40] have studied the effect of nanoparticles on the convective heat transfer of nanofluids in a porous medium. They found that the presence of nanoparticles in the porous media may suppress some of the natural convective heat transfer mechanisms. In another study Sheremet et al. [39] have analyzed the natural convective heat transfer of nanofluids in a cavity containing a hot solid block. The results show

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Nomenclature

A_{mush}	mushy-zone constant (Carman–Koseny equation constant)
C_p	specific heat in constant pressure ($J/kg\,K$)
Fo	non-dimensional time
g	gravity (m/s^2)
H	length and height (m)
k	thermal conductivity ($W/m\,K$)
L	latent heat of fusion (J/kg)
Nc	conductivity parameter
$N\nu$	viscosity parameter
P	pressure (Pa)
Pr	Prandtl number
Ra	Rayleigh number
S	enclosure inclination angle
$S(T)$	Carman–Kozeny equation (source term)
Ste	Stefan number
t	time (s)
T	temperature (K)
T_f	melting temperature (K)
u	velocity in the x-direction (m/s)
$\mathbf{u}$	velocity vector (m/s)
v	velocity in the y-direction (m/s)
x,y	Cartesian coordinates

Greek symbols

(T)φ	liquid fraction
α	thermal diffiusivity (m^2/s)
ϕ	Volume fraction of nanoparticles
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
ε	Carman–Kozeny equation constant
υ	kinematic viscosity (m^2/s)
TΔ	mushy-zone temperature range (K)
ξ	basis functions
γ	the ratio of thermal diffiusivity
β	thermal expansion coefficient (1/K)
θ	on-dimensional temperature

Subscripts

bf	base fluid
c	cold
F	fusion
h	hot
hnf	hybrid nanofluid
i	interface position
k	node number
l	liquid phase
nf	nanofluid
p	particles
s	solid phase

the enhancement of heat transfer in the presence of nanoparticles. Additionally, phase change phenomena in nanofluids have been addressed by different researchers. Malvandi et al. [30] studied the film-wise condensation of nanofluids over a vertical plate. In order to modify the cooling rate, the thermophysical properties of nanofluids are subjected to change, and also the flow and heat and mass transfer are controlled throughout the domain. It is found that increasing nanoparticles volume fraction and normal temperature difference enhance the heat transfer rate, and it is also reported that the alumina nanoparticles offer better cooling performance compared to titania. In another attempt, the anisotropic behavior of magnetic nanofluids in film-wise condensation is investigated by Heysiattalab et al. [18] over a vertical plate. In this study, the modified Buongiorno model is used to observe the effects of nanoparticles slip velocity relative to the base fluid. It is reported that the heat transfer rate enhances when the magnetic field is aligned in the direction of the temperature gradient.

An augmentation in the thermal conductivity of a composite PCM has been reported by Zeng et al. [49] by using Ag nanoparticles. Liu et al. [27] reported a significant enhancement in the thermal conductivity of a PCM by suspending a small amount of TiO_2 nanoparticles in saturated $BaCl_2$. The effects of different nanoparticles such as Cu, Al, and C/Cu on the heat transfer rate of paraffin as a nano-enhanced phase-change material (NEPCM) have been investigated by Wu et al. [47]. They found that the heating and cooling times decreased by 30.3% and 28.2%, respectively, using a 1% Cu nanoparticles. Harikrishnan and Kalaiselvam [17] studied the solidification and melting time for the different volume fractions of CuO in an oleic phase-change material. They reported up to 27.67% and 28.57% reduction in solidification and melting times, respectively. These investigations have been done using single metallic or non-metallic nanoparticles. The non-metallic particles such as Al_2O_3 have an excellent stability and chemical inertness, although, they have lower thermal conductivities compared to the metallic nanoparticles.

Incorporation of a small amount of metal particles with non-metallic particles can outstandingly enhance the thermal properties. A copper–alumina composite briquette has been prepared by Jena et al. [20] from a homogeneous mixture of finely divided CuO and Al_2O_3 using the hydrogen reduction technique. The results reported by Suresh et al. [42] indicate that the augmentation in the viscosity is considerably higher than the increase in the thermal conductivity. A maximum enhancement of 13.56% in the Nusselt number has been reported by Suresh et al. [43] for Al_2O_3–Cu hybrid nanofluid. Esfe et al. [12] investigated the effect of nanoparticles volume fraction on the thermal conductivity and the dynamic viscosity. They utilized Ag–MgO/water hybrid nanofluid with nanoparticles volume fraction range between 0% and 2%, and then examined the accuracy of different existing theoretical and empirical correlations in predicting the value of the thermal conductivity and dynamic viscosity by comparing the predicted values with experimental data. Moghadassi et al. [33] numerically studied the effects of water-based Al_2O_3 and Al_2O_3–Cu hybrid nanofluid with a 0.1% volume concentration on laminar forced convective heat transfer. Their results revealed a much higher convective heat transfer coefficient for the hybrid nanofluid.

In view of the importance of phase-change materials and the beneficial characteristics of hybrid nanoparticles, the aim of the present research is to analyze the effect of a hybrid nanofluid on natural convection inside an enclosure which is filled with nano-enhanced phase-change material. The present study aims to answer the following questions regarding to phase change heat transfer of single/hybrid nanofluids:

I Does the presence of nanoparticles enhance the melting rate?
II From the literature review, it is clear that the presence of nanoparticles enhances the thermal conductivity and the dynamic viscosity of the NEPCM. The increase of the thermal conductivity tends to increase the heat transfer and the melting rate. In contrast, the increase of the dynamic viscosity tends to suppress the natural convective heat transfer. How does these two properties simultaneously affect the melting process of a NEPCM?
III What is the effect of the increase of the volume fraction of solid nanoparticles on the melting rate?