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Original Research Paper

Phase-change heat transfer of single/hybrid nanoparticles-enhanced phase-change materials over a heated horizontal cylinder confined in a square cavity

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ABSTRACT

The melting process of a nano-enhanced phase-change material is investigated in a square cavity with a hot cylinder located in the middle of the cavity in the presence of both single and hybrid nanoparticles. The dimensionless partial differential equations are solved numerically using the Galerkin finite element method using a grid with 6000 quadrilateral elements. The effects of the volume fraction of nanoparticles, the Fourier number, the thermal conductivity parameter, and the viscosity parameters are studied. The results show that the solid-liquid interface and the liquid fraction are significantly affected by the volume fraction of nanoparticles and the thermal conductivity parameter. Additionally, it is found that the melting rate is much larger when the Fourier number changes between 0 and 0.5 and a further increase in the Fourier number causes a reduction in the rate of the melting.

1. Introduction

Natural convection caused by a circular cylinder inside an enclosure has a variety of applications in engineering systems such as compact heat exchangers, solar collectors, cooling of electronic devices, chemical reactors. Cesini et al. [1] conducted a numerical and experimental study of the natural convection induced by a horizontal cylinder in a rectangular cavity. Yoon et al. [2] reported the natural convection results from two hot circular cylinders inside a cavity. They found that the bifurcation from steady state to unsteady state natural convection significantly depends on the location of the inner cylinders and the Rayleigh number. Huang et al. [3] investigated the natural convection caused by a time-periodic pulsating temperature of a cylinder inside a square cavity. They reported an enhancement in the heat transfer compared to the steady state natural convection. Zhang et al. [4] numerically studied the effects of an elliptic cylinder on the natural convection inside a square cavity using the Galerkin method.

One of the reliable ways of storing energy is using Phase Change Materials (PCMs). This is due to the fact that a small volume of PCMs can store a substantial amount of energy during the phase-change process. The phase-change materials are now widely used in a variety of applications such as cooling of electronic devices [5] in various fields of thermal management of high power electronics [6], cooling of mobile electronic devices [7], cooling enhanced by heat pipes [8]. An excellent review on thermal management systems using phase-change materials for electronic components has been reported by Ziye et al. [9]. The phase-change materials have also found important applications in solar heating systems [6,9]. An extensive review of the applications of phase-change materials has been addressed by Sharif et al. [10]. Also, PCMs have been utilized in waste heat recovery systems [11].

Despite the fact that the phase-change materials are now widely used in a variety of applications, they have a weak thermal conductivity causing a reduction in the performance of the energy storage unit. Luckily, the thermal conductivity of the PCMs can be enhanced using nanofluids. Zeng et al. [12] reported an enhancement in the thermal conductivity of a composite PCM using Ag nanoparticles. A significant augmentation in the thermal conductivity of PCMs was reported by Liu et al. [13] by utilizing a small volume fraction of TiO_2 nanoparticles in saturated $BaCl_2$. Wu

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Nomenclature

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

Greek symbols

φ (T)	liquid fraction
α	thermal diffusivity (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)
ΔT	mushy-zone temperature range (K)
ξ	basis functions
γ	the ratio of thermal diffusivity
β	thermal expansion coefficient (1/K)
θ	non-dimensional temperature

Subscripts

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

et al. [14] found that the heating and cooling times declines up to 30.3% and 28.2% exploiting 1% of Cu nanoparticles in paraffin. Harikrishnan and Kalaiselvam [15] reported a reduction up to 27.67% and 28.57% in the solidification and melting time using CuO in oleic phase-change material. The nanofluids in liquid form have also been studied in many recent studies. For instance, different heat transfer aspects of nanofluids including mixed convection in micro channels [16], film condensation [17] and the effect of magnetic fields on the heat transfer of nanofluid [18,19] and natural convection in enclosures [19,20] and non-Newtonian nanofluids [21].

The aforementioned studies have been done utilizing a single metallic or non-metallic nanoparticles. The metallic nanoparticles are known for their high thermal conductivity, however, their tendency to chemical reactions make them an unreliable choice. On the other hand, the non-metallic particles have a high stability and chemical inertness, albeit, they possess a weak thermal conductivity. Recently, it is suggested to combine a small amount of metallic nanoparticles with non-metallic nanoparticles causing an enhancement in the thermal properties of the base fluid. Suresh et al. [22] reported a considerably higher augmentation in the viscosity compared to the thermal conductivity using Al_2O_3–Cu hybrid nanoparticles. Suresh et al. [23] reported a maximum enhancement of 13.56% in the Nusselt number by using an Al_2O_3–Cu hybrid nanofluid. Yarmand et al. [24] reported a maximum 32.7% enhancement in the values of the Nusselt number using a GNP–Ag/water hybrid nanofluid. Takabi and Salehi [25] numerically investigated the effects of Al_2O_3–Cu/water hybrid nanofluids inside a sinusoidal corrugated enclosure. They reported higher enhancement in the heat transfer rate using a hybrid nanofluid compared to a regular nanofluid. Takabi and Shokouhmand [26] numerically studied the effects of an Al_2O_3–Cu/water hybrid nanofluid on the heat transfer rate in the turbulent regime. It was found that the hybrid nanofluid causes improvements in the heat transfer rate and also it has an undesirable effect on the friction factor which causes higher pressure drop in the hybrid nanofluid. The effects of Al_2O_3–Cu/water hybrid nanofluid over a stretching sheet was numerically investigated by Surya and Anjali [27]. It was shown that the Al_2O_3–Cu/water hybrid nanofluid has a higher heat transfer rate compared to the Cu/water nanofluid even in the presence of a magnetic field.

Due to the significant importance of phase-change materials and their applications in the energy storage systems and the fact that nano-enhanced phase-change materials could increase the performance of an energy storage system, the authors of the present study feel necessary to conduct the present research. In this paper, the effects of hybrid and single nanoparticles on the melting process of nano-enhanced phase-change materials are investigated inside a square cavity for the first time. The melting is caused by a hot cylinder located in the center of the cavity. The governing set of equations has been solved numerically using the Galerkin finite element method using 6000 quadrilateral elements. The results of the present study are compared with both experimental and numerical results available in the literature. The authors hope that the results of the present study could help to improve the design and the functionality of energy storage systems in the future. To the best of the authors' knowledge, the results of the present paper are unique and the authors hope that the results of this paper help to design much efficient energy storage systems in the future.

2. Geometric and mathematical models

2.1. Physics of the problem

As shown in Fig. 1, the schematic of a horizontal cylinder in a square cavity, A concentric heated circular cylinder of radius R