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Melting of nano-phase change material inside a porous enclosure

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ABSTRACT

The melting process of a nano-phase change material (or nano-PCM) in a square enclosure filled with a porous medium was investigated numerically and analytically. The dimensionless continuity, Darcy–Brinkman momentum, and energy equations were solved using the finite element method. One vertical wall of the square enclosure was heated at a constant temperature (T_h), while all the other walls were insulated. The numerical results were adopted for a wide range of Rayleigh number ($10^6 \leqslant Ra \leqslant 5 \times 10^7$), Darcy number ($10^{-8} \leqslant Da \leqslant 10^0$), and the volume fraction of nanoparticles (ϕ = 0%, 10%, and 20%). The results were expressed in terms of isothermal lines, streamlines, and Nusselt number. In addition, a scale analysis of the governing equations was performed to verify the numerical results. A validation was performed between the present study and previously reported results in the literature; a good agreement was achieved. The numerical results indicated that the melting process is improved by increasing *Ra*, ϕ, and *Da*. The scale analysis successfully predicted the behavior of the meting process of nano-PCM embedded in the porous medium.

1. Introduction

Thermal storage is a key component in many engineering applications. Solar power plants [1] and domestic usage [2] are two common application examples. In many applications, thermal storage balances between the demand and the supply of energy which has made the thermal storage an attractive research field for the last 30 years. The thermal energy may be stored in sensible or latent forms. The sensible thermal storage has high storing ability; however, high mass and volume of sensible materials are required to store a reasonable amount of heat [3]. Latent thermal energy storage has many attractive features, such as, nearly isothermal charging and discharging processes besides the low ratio of volume to energy [4]. These attractive features make the PCM a preferred option in many engineering applications, such as, energy storage, air-conditioning, thermal management, medical appliances, and chemical reactions [5]. However, the low thermal conductivity of PCMs decreases the heat transfer rate during charging and discharging cycles [6]. Therefore, many improvements have been proposed in the existing literature to increase the thermal conductivity of PCM. One of the first proposed improvements is immersing metallic porous medium in a PCM by Kazmierczak et al. [7] as reported by Nield and Bejan [8]. The most recent proposed method is adding high thermal conductivity metallic nanoparticles to PCM [9]. The improvement of PCM performance was reviewed by researchers in terms of utilizing porous medium [10] or nanoparticles [11].

Utilization of porous medium is one of the heat transfer enhancing mechanisms that researchers have studied to overcome the low thermal conductivity of PCMs. Beckermann and Viskanta [12] numerically and experimentally investigated melting and solidification of gallium by immersing glass beads in a square enclosure. Their results revealed that during melting and solidification processes the interface movement and shape are highly influenced by natural convection in the liquid portion and conduction in the solid portion of PCM. Lafdi et al. [13] conducted an experimental study to measure the temperature field and capture the interface motion using paraffin PCM and aluminum foams. Lafdi et al. [13] recommended optimal values for foam porosity and pore size to enhance the thermal performance as porosity and pore size influence heat conduction and convection. Both higher porosity and bigger pore size accelerate reaching the thermal steady state. The early thermal steady state occurs because of the greater impact of convection associated with high porosity and larger pore size foams. Authors also found that the heat conduction dominates in case of lower porosity foam. Zhao et al. [14] conducted an experimental and numerical study to investigate the heat transfer during the melting and solidification of paraffin wax embedded within copper metal foams. The use of porous medium improves the heat

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Nomenclature

b	height of the convection dominated liquid region (m)
c_p	specific heat at constant pressure (J/kg K)
D	melting front position, m
Da	Darcy number based on the enclosure size, $Da = K/L^2$
Da_b	Darcy number based on the height of the convection dominated liquid region, $Da = K/b^2$
Fo	Fourier number, $Fo = k_{eff}t/\rho_{nf}c_{p,nf}L^2 = \alpha_{eff}t/L^2$
g	gravitational acceleration (m/s^2)
h	convection heat transfer (W/m^2)
h_f	latent heat of fusion (J/kg)
K	permeability (m^2)
k	thermal conductivity (W/(m K))
L	enclosure height (m)
l	width of the remaining solid (m), dimensionless melting front position
Nu	Nusselt number, defined in Eq. (19)
P	dimensionless pressure
p	pressure (Pa)
Pr	Prandtl number, $\Pr = \upsilon_{nf}/\alpha_{eff} = \mu_{nf}/\rho_{nf}\mu_{eff}$
$\dot{Q}$	total heat transfer rate per unit width (W/m)
Q''	heat transfer flux rate (W/m^2)
Ra	Rayleigh number based on the enclosure size, $Ra = g(\rho\beta)_{nf}L^3(T_h - T_m)/\mu_{nf}\alpha_{eff}$
Ra_b	Rayleigh number based on the height of the convection dominated liquid region, $Ra_b = \rho^2 g\beta_{nf}b^3(T_h - T_m)/\mu_{nf}^2$
Ste	Stefan number, $Ste = c_{p_{nf}}(T_h - T_m)/h_{f_{nf}}$
Ste^*	modified Stefan number for the porous medium case, $Ste^* = Ste/\varepsilon = c_{p_{nf}}(T_h - T_m)/\varepsilon h_{f_{nf}}$
T	temperature (K)
t	time (s)
U	dimensionless volume-averaged velocity of the liquid nano-PCM in the X-direction
u	volume-averaged velocity of the liquid nano-PCM in the x-direction (m/s)
V	dimensionless volume-averaged velocity of the liquid nano-PCM in the Y-direction
v	volume-averaged velocity of the liquid nano-PCM in the y-direction (m/s)
X	dimensionless horizontal coordinate
x	horizontal coordinate (m)
Y	dimensionless vertical coordinate
y	vertical coordinate (m)
z	the height of the remaining solid portion in the enclosure (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
δ_b	thermal boundary layer thickness in convection zone of height b (m)
δ_T	thermal boundary layer thickness (m)
ε	Porosity
θ	dimensionless temperature
μ	dynamical viscosity (Pa s)
ρ	density (kg/m^3)
σ	the ratio of the heat capacitances of the porous medium and nano-PCM, $\sigma = (\rho c_p)_{eff}/(\rho c_p)_{nf}$
υ	kinematic viscosity (m^2/s)
ϕ	volume fraction of nanoparticles

Subscripts

avg	average
cond	conduction
conv	convection
f	PCM
eff	effective nano-PCM properties inside the porous medium
h	hot
lat	latent
m	melting temperature
n	nanoparticle
nf	nano-PCM
s	solid porous medium

transfer in the solid phase. The overall heat transfer rate may be increased 3–10 times by using copper foam. In addition, the solidification of PCM embedded in copper metal foams requires half of the time of solidification of PCM without metal foams. Py et al. [15] experimentally and theoretically investigated the influence of a natural graphite matrix on the thermal performance of paraffin. The thermal conductivity of the 'graphite matrix + PCM' has significantly improved from 0.24 W/m K (for the pure PCM) to a 4–70 W/m K (for the combination) depending on the paraffin weight fraction. In addition, higher solidification rate and decreasing thermal storage power stabilization were achieved. Through their numerical study, Mesalhy et al. [16] found that a low porosity matrix accelerates the melting process; however, low porosity also damps the convection currents. Mesalhy et al. [16] concluded that the utilization of high thermal conductivity and high porosity matrix significantly improves the melting process of PCM.

The porous medium increases the area-volume ratio, but it reduces the volume fraction of the utilized PCM. Besides, the improvement in natural convection heat transfer of a fluid by adding nanoparticles [17,18] has encouraged researchers to investigate the effect of adding nanoparticles on the melting and solidification of PCM. Arasu and Mujumdar [19] performed numerical simulations of paraffin wax with the addition of metallic nanoparticles, Al_2O_3, in a square enclosure. Arasu and Mujumdar [19] found that the liquid nano-PCM flow and the solid–liquid interface shape are affected by the thickness of the liquid PCM layer. Increasing the volume fraction of Al_2O_3 decreases the melting rate. Heating the vertical side of the enclosure enhances the free convection effect thus increasing the melting rate and energy stored when compared to the heating from below case. The researchers concluded that the effective thermal conductivity of the paraffin wax is improved by using smaller volume fractions of Al_2O_3. Darzi et al. [20] incorporated Cu nanoparticles in water to improve the heat transfer throughout the melting process. Authors indicated significant enhancement in the thermal conductivity of PCM with nanoparticles compared to pure PCM. Darzi et al. [20] concluded that the improvement in the thermal conductivity of nano-PCM and the reduction in the latent heat of fusion lead to a faster heat transfer rate. Ho and Gao [21] conducted experiments to investigate the melting of n-octadecane with suspended Al_2O_3 nanoparticles. Their results revealed that increasing the mass fraction of nanoparticles suspended in nano-PCM decreases the natural convection effect in the melted region when compared to the pure PCM. Hosseini et al. [22] performed a numerical study to investigate the effects of nanoparticle dispersion on solidification of three mixtures of nanofluids; Cu–water, TiO_2–Water, and Al_2O_3–water. The authors found that for 0.2% volume fraction of Cu nanoparticles, a decrease of 16% in solidification time