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Research Paper

Transient behavior analysis of the melting of nanoparticle-enhanced phase change material inside a rectangular latent heat storage unit

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HIGHLIGHTS

- Melting of nanoparticle-enhanced phase change in a rectangular latent heat storage unit is investigated numerically.
- Melting time decreases with increasing volumetric fraction of nanoparticles.
- Melting time decreases with increasing Rayleigh number.
- Melting time decreases with increasing aspect ratio of NEPCM slabs.
- Melting time decreases with increasing Reynolds number.

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ABSTRACT

Melting of Paraffin Wax (P116) dispersed with Al2O3 nanoparticles in a rectangular latent heat storage unit (LHSU) is numerically investigated. The storage unit consists of a number of vertical and identical plates of nanoparticle-enhanced phase change material (NEPCM) separated by rectangular channels through which a heat transfer fluid flows (HTF: Water). A two-dimensional mathematical model is considered to numerically investigate the heat and flow characteristics of the LHSU. The heat transfer and fluid flow during the melting process were formulated using the enthalpy-porosity method. The finite difference forms of the governing equations are obtained using the finite volume approach. The numerical model has been validated by experimental, theoretical and numerical results available in the literature. The effects of the aspect ratio of NEPCM slabs, volumetric fraction of nanoparticles, Reynolds number and Rayleigh number on the flow characteristics and thermal performance of the storage unit were investigated. A correlation including all these investigated control parameters has been developed to predict the time required for the complete melting of NEPCM.

1. Introduction

Due to their high energy storage capacity, the latent heat storage units using phase change materials (PCMs) have gained great attention over the last three decades. However, the phase change materials (PCMs) are characterized by a low thermal conductivity which limits the heat exchange rate and slowed their melting/solidification rate. To overcome this drawback and improve the heat transfer rate during the solid-liquid phase change process, several methods have been suggested in the literature. These methods include the dispersion of nanoparticles with a very high conductivity in PCMs [1], integration of metal matrix in PCMs [2], use of multiple PCMs [3,4] and porous matrix [5]. Among these methods, the dispersion of high conductivity nanoparticles in PCM is the main topic of this study.

In recent years, a number of experimental, numerical and theoretical works have been performed to investigate the thermal performance of nanoparticles enhanced phase change materials. Dhaidan [6] presented a review on the experimental, numerical and theoretical investigations of the melting of NEPCM inside various shape containers including rectangular, spherical and cylindrical enclosures. The author reported the effect of the geometrical parameters and operational conditions on the heat transfer and melting characteristics. The results show that the increase of the amount of nanoparticles dispersion in PCMs enhances heat transfer rate and reduces the melting time. Khodadadi and Hosseinizadeh [7] studied numerically the improving of the functionality of phase change material (PCM: water) by dispersion of nanoparticles (copper) during the solidification process with natural convection in a square cavity. The results of this study showed that the use of

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Nomenclature

A	aspect ratio, H/(d/2)
c_p	specific heat at constant pressure (J/kg K)
d	thickness of the PCM slabs (m)
d_n	diameter of nanoparticles (m)
$\bar{d}_n$	dimensionless diameter of nanoparticles, d_n/l_o
D_h	hydraulic diameter (m), $D_h = 2w\,e/(w + e)$)
$\overline{D}_h$	dimensionless hydraulic diameter, D_h/l_o
e	depth of the storage unit (e = 1 m)
f	liquid fraction
g	acceleration of gravity (m/s^2)
h	specific sensible enthalpy (J/kg)
H	height of the PCM slabs (m)
k	thermal conductivity (W/m K)
$\bar{k}$	dimensionless thermal conductivity, $k/k_{m,l}$
l_0	characteristic length, $l_0 = \sqrt{Hd/2}$
p	pressure (Pa)
q	dimensionless heat transfer rate
Q	dimensionless heat
Ra	Rayleigh number
Re	Reynolds number
Ste	Stefan number
S_u	source term for u momentum equation
S_v	source term for v momentum equation
S_h	source term for energy equation in terms of enthalpy
T	temperature (K)
t	time (s)
u, v	velocity components (m/s)
U, V	dimensionless velocity components
x, y	Cartesian coordinates (m)
w	thickness of the HTF channels (m)

Greek symbols

α	thermal diffusivity (m^2/s), $\alpha = k/\rho c_p$
$\bar{\alpha}$	dimensionless thermal diffusivity, $\alpha/\alpha_{m,l}$
ϕ	volumetric fraction of nanoparticles
β	coefficient of thermal expansion of liquid PCM (K^{-1})
θ	dimensionless temperature
τ	dimensionless time
μ	dynamic viscosity (N s/m^2)
ν	kinematic viscosity (m^2/s)
Δh	latent heat (J/kg)
ρ	density (kg/m^3)
ε	storage efficiency
Ψ	dimensionless stream function

Subscripts

e	inlet
f	heat transfer fluid (HTF)
l	liquid
lat	latent
melt	melting
n	nanoparticle
nm	Nanoparticle-enhanced phase change material (NEPCM)
m	PCM
o	outlet
P	node point
s	solid
sen	sensible

Superscripts

k	iteration k
0	old value at previous time step

NEPCM improves the heat release compared to a basic PCM. Ho and Gao [8] experimentally studied the melting in a square enclosure filled with PCM (*n*-octadecane) dispersed with alumina nanoparticles (Al_2O_3). They reported that the influence of the solid subcooling through the un-melted PCM can be further enhanced by dispersion of high conductivity nanoparticles in the enclosure. They also indicated that the natural convection heat transfer in the liquid region degrades significantly with the increase of the mass fraction of nanoparticles when compared with natural convection corresponding to a base PCM. Sebti et al. [9] conducted a 2D numerical study to investigate the heat transfer enhancement during melting process in a square enclosure through dispersion of nanoparticles. These authors reported that the dispersion of nanoparticles decreases the melting time. They also reported that the increase of the difference between the melting point and the hot wall temperature leads to a significant decrease of the melting time. Hossain et al. [10] developed a two dimensional thermal model to study the melting process of NEPCM inside a rectangular porous medium. The results show that the NEPCM melts rapidly within the lower porosity medium. Shuja et al. [11] performed an experimental and numerical investigations on the thermal characteristics of PCM (*n*-octadecane) integrated with metallic meshes. They examined the effect of the mesh geometry on the melting time for two different metallic mesh arrangements. The results show that the melting time of PCM is the shortest for the triangular mesh geometry then followed by the rectangular and hexagonal meshes. Sciacovelli et al. [12] conducted a numerical analysis of the melting of NEPCM in a shell-and-tube latent heat storage unit (LHSU). They demonstrate that the melting time is reduced by 15% when the volume fraction of dispersed nanoparticles is 4%. Kashani et al. [13] numerically studied the effects of the nanoparticles volume fraction and cold wall temperature during the solidification of NEPCM filled in a rectangular enclosure. They found that a large solid fraction is obtained for a smaller wall temperature and a high nanoparticles volume fraction. Hosseinizadeh et al. [14] conducted a numerical study of the melting of NEPCM inside a spherical container. The simulation results of this study show a pronounced potential of using phase change material with dispersed nanoparticles. Jourabian et al. [15] numerically examined the melting of Cu/water NEPCM inside a cylindrical horizontal annulus by using the enthalpy-based Lattice Boltzmann method. Their results show that owing to the enhancement of the thermal conductivity, the effect of the volume fraction of nanoparticles on the heat transfer rate is more significant. Their results also indicate that the temperature distribution in the NEPCM is faster than that of a base PCM. Ranjbar et al. [16] numerically studied the heat transfer enhancement in the LHSU through dispersion of nanoparticles during the solidification process. They reported that the increase in the volume fraction of the dispersed nanoparticles substantially increases the heat transfer rate. They also found that the dispersion of high conductivity nanoparticles promotes the heat transfer by conduction in NEPCM. Elbahjaoui et al. [17] investigated numerically the melting of PCM dispersed with alumina nanoparticles in a thermal storage unit composed of a number of vertical and identical slabs separated by HTF fluid flow. They evaluated the effect of the volumetric fraction of nanoparticles, HTF inlet temperature and mass