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Numerical study on the effect of non-uniform magnetic fields on melting and solidification characteristics of NEPCMs in an annulus enclosure

M. Rostami Dibavar[a], M. Mohammadpourfard[b,*], F. Mohseni[c], S. Zeinali Heris[b,*]

[a] Department of Mechanical Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran
[b] Faculty of Chemical and Petroleum Engineering, University of Tabriz, Tabriz, Iran
[c] Rue de Gibraltar 12, Neuchatel 2000, Switzerland

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ABSTRACT

In this study, the effects of non-uniform magnetic fields on melting and solidification of Nanoparticle-Enhanced Phase Change Materials (NEPCM) in an annulus enclosure are numerically investigated. Magnetic fields are applied on electrically conductive magnetic nanofluids by positioning a wire carrying the electric current in the center of the annulus. For the numerical simulation, a homogenous single-phase model and finite volume method are used and the melting and solidification processes are studied using the enthalpy-porosity method, where, instead of explicitly tracking the liquid-solid interface, the so-called liquid fraction quantity is computed based on the enthalpy balance in each cell and in each time iteration. The results show that, for the case with non-electrical conductive magnetic nanofluids, by increasing the magnetic number, the time required for the melting and solidification processes are reduced up to 39.91% and 14.29%, respectively. However, for the case with electrical conductive magnetic nanofluids at $Ra = 10^4$ and at specific magnetic numbers, the rate of both melting and solidification processes decreases by increasing the Hartmann number.

1. Introduction

Increasing greenhouse gases emissions and decreasing fossil fuel sources in recent years have led to many investigations on finding new and renewable energy resources. Most of the energy generation by renewable resources (wind and solar) are dependent on weather conditions and present a high variability being its generation profile very different from the energy demand profile. Therefore, developing new energy storage systems using Phase Change Materials (PCMs) is considered to be one of the solutions to store the generated energy to be consumed when needed, as these materials, during phase transition, could absorb and release energy at a constant temperature. Nowadays, PCMs are used in many industrial applications where melting and solidification plays an important role [1].

The ideal PCM is stable, chemically inert, and non-flammable, it should also remain solid through the phase change, and have a high latent heat of phase change as well as high thermal conductivity to maximize the efficiency of the heat-transfer during the phase change. Having a high latent heat is also one of the advantages of using these materials which results in their high energy storage capacity. Unfortunately, many materials which would otherwise make very attractive PCMs, such as paraffin and natural oils, e.g., coconut oils, are flammable, lose structural integrity during their phase change and suffer from having a low thermal conductivity. Therefore, researchers have used many heat transfer enhancement techniques, e.g., extended surfaces or fins, to optimize the heat transfer rate [2].

PCMs are categorized, based on their phase transition temperatures into: Eutectics, salt hydrates and organic materials. The materials with melting temperatures below 15 °C are used for cooling and air conditioning, the materials with melting temperatures higher than 90 °C are used to avoid sudden increase in temperature, e.g., to prevent fire initiation and the materials with melting temperatures between these values can be used to store solar energy as well as electric heating systems.

Elgafy and Lafdi [3] studied experimentally and analytically thermal performance of nanocomposite carbon nanofibers filled paraffin wax. They found that nanocomposite thermal conductivities were enhanced significantly causing the cooling rate to increase. Alawadhi [4] studied numerically solidification process of water inside an elliptical enclosure using the finite element method based on a fixed grid scheme. It was indicated that solidification time is considerably decreased with increasing the aspect ratio of the ellipse, but the inclination has a negligible effect on the solidification process.

One of the main drawback of many PCMs are their low thermal

* Corresponding authors.
E-mail addresses: Mohammadpour@tabrizu.ac.ir (M. Mohammadpourfard), s.zeinali@tabrizu.ac.ir (S. Zeinali Heris).

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Nomenclature

a	sensible enthalpy (J/kg)
A	enthalpy (J/kg)
A_{mush}	mushy zone constant
$\vec{B}$	magnetic field induction vector(T)
c_p	specific heat(J/kg K)
d_p	magnetic particle diameter(m)
Ec	Eckert number$\left(=\frac{\mu_f \alpha_f}{(\rho c_p)(T_h - T_c) l^2}\right)$
F	external force
g	gravitational acceleration(m/s^2)
$\vec{H}$	magnetic field intensity vector(A/m)
Ha	Hartmann number$\left(=l\mu_0 H_0 \sqrt{\frac{\sigma_f}{\mu_f}}\right)$
I	current intensity (A)
k	thermal conductivity$\left(\frac{\text{W}}{\text{mK}}\right)$
K_B	Boltzmann constant(1.3806503 × 10^{-23} J/K)
l	length($=R_2 - R_1$)
L	Langevin function
L_h	latent heat of liquid PCM
m_p	particle magnetic moment(Am^2)
M	magnetization(A/m)
Mn	magnetic number$\left(=\frac{\mu_0 \chi H_0^2 l^2}{\rho_f \alpha_f^2}\right)$
M_s	saturation magnetization(A/m)
P	pressure (Pa)
Pr	Prandtl number$\left(=\frac{\upsilon_f}{\alpha_f}\right)$
Ra	Rayleigh number$\left(=\frac{g\beta_f l^3 (T_h - T_c)}{\alpha_f \upsilon_f}\right)$
$\vec{S}$	source terms of enthalpy porosity method
T	temperature (K)
T_c, T_h	cold and hot wall temperature
u, v	velocity components in the x-direction and y-direction(m/s)
U, V	dimensionless velocity components in the x-direction and y-direction(m/s)
x, y	coordinate axis (m)
X, Y	dimensionless coordinate axis (m)

Greek symbols

α_f	thermal diffusivity(m^2/s)
α_p	particle volume fraction
β	thermal expansion coefficient(K^{-1})
γ	liquid fraction
ε	temperature number
θ	dimensionless temperature
μ	dynamic viscosity(kg/m s)
μ_0	magnetic permeability in vacuum(=4π × 10^{-7}T. m/A)
ξ	Langevin parameter
ρ	density(kg/m^3)
σ	electrical conductivity(s/m)
χ	magnetic susceptibility

Subscripts

f	fluid
nf	nanofluid
p	nano particles

conductivities which can influence the time of melting and solidification, i.e., time of charging and discharging of the storage system. Due to the recent progresses in the field of nanotechnology and since metal nanoparticles have high thermal conductivities, it has been shown that PCMs including nanoparticles, so-called Nanoparticle-enhanced phase change materials (NEPCMs), have higher thermal conductivities [5].

Khodadadi and Hosseinizade [6] have shown that adding copper nanoparticles to water, in a square enclosure, leads to an enhanced heat transfer in the PCM during solidification. Wu et al. [7] investigated experimentally the thermal energy storage capacity of water and Al_2O_3 nanoparticles for cooling applications. They showed that the degree of water cooling and progression of solidification time is reduced by adding Al_2O_3 nanoparticles in water.

Kibria et al. [8] studied the changes in the thermophysical properties of PCMs due to the dispersion of nanoparticles. They compared different types of nanoparticles and reported a better performance of carbon nanotubes and nanofibers, in terms of improving the thermal properties of PCMs, compared to the other type of nanoparticles assessed. Wu et al. [9] studied experimentally the melting and solidification characteristics of Paraffin when copper nanoparticles are added. They showed that, by adding 2% mass fraction of the nanoparticles, its thermal conductivity increases up to 14.2% in the solid phase and 18.1% in the liquid phase. Also, they showed that melting and solidification time decreases by adding 1% mass fraction of copper nanoparticles to the pure paraffin.

Zheng Li et al. [10] used a lattice Boltzmann method with an interfacial tracking method to solve the melting problem in an enclosure. Their results showed that both conduction and convection controlled melting problems agreed very well with those in the literature. Arasu et al. [11] studied numerically the effect of the volume fraction of CuO and Al_2O_3 nanoparticles on the melting and solidification rate of paraffin wax. They concluded that the dispersion of nanoparticles in low volume fractions increases the heat transfer rate. This enhancement is shown to be more pronounced for the Al_2O_3 nanoparticles compared to the CuO nanoparticle.

In addition, increase in the performance of paraffin wax with Al_2O_3 nanoparticles in a concentric pipe heat exchanger is numerically studied in [12]. They demonstrated that the charge and discharge rate can be improved by adding the nanoparticles. Arasu and Mujumdar [13] investigated experimentally the melting of paraffin wax dispersed with Al_2O_3 nanoparticles in a square enclosure which is heated from the bottom as well as the vertical side of the enclosure. They showed that melting rate can be significantly increased for the case with a low volume fractions of Alumina. Also, they reported that melting and energy storing rate is higher for the case with the heated vertical side compared to the heating from the bottom.

Feng et al. [14] investigated numerically melting of water with copper nanoparticles in a rectangular cavity which is heated from the bottom, using a Lattice Boltzmann method. They studied the effects of the nanoparticles volume fraction and Grashof number on the flow structure and the heat transfer properties and found higher heat transfer efficiencies for the NEPCMs compared to the pure PCMs. They also reported that, by increasing the nanoparticles volume fraction, a bigger portion of the temperature field and the melting front is engaged and both the liquid fraction and the energy storage increase. Melting of N-octadecane with CuO nanoparticles in a square container, which is heated from one side with a constant heat flux while the other sides are insulated, is numerically and empirically investigated by Dhaiden et al. [15]. Their experimental and numerical results showed that adding the nanoparticles increases heat transfer rate and consequently the phase transition completion time in the container. They also reported that, by increasing the applied heat flux, e.g., increasing the Rayleigh number, melting process accelerates.

In a similar study, Dhaiden et al. [16] studied experimentally and numerically melting of N-octadecane with dispersed copper nanoparticles. The results showed that the melting characteristics, such as