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Numerical Investigation of Non-Uniform Magnetic Fields Effects on Heat Transfer and Development of Melting- Solidification Processes in an Enclosure

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ABSTRACT: Developing new energy storage systems using Phase Change Materials (PCMs) have been recently attracted considerable interest, since these materials during phase transition, could absorb and release energy at a constant temperature. Due to this feature, they are widely used in energy systems. In this investigation, the effects of applying nonuniform magnetic field with negative and positive gradients on the heat transfer and also on the development of solidification and melting processes of a non-electrical conductive magnetic nano-fluid as a PCM in an enclosure in the presence of different magnetic fields have been studied numerically using single phase homogenous model and control volume technique. In the present study, the enthalpy-porosity method has been used for analyzing the solidification and melting process of phase change materials enhanced with nanoparticles (in this study Fe3O4 nanoparticles have been used). The obtained results show using nanoparticles and applying magnetic fields increase the development of solidification and melting processes. Due to heat transfer through vertical walls, the effect of the magnetic field with positive and negative gradients only in the y-axis direction has been investigated. Since the magnetic field is applied only to the mushy zone, a magnetic field with a negative gradient in the vertical axis direction will have the greatest effect on the progression of the solidification and melting process so that the time of these processes will be decreased.

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1- Introduction

Today with regard to increase in the demand for energy and limitation of fossil fuels, many scientists around the world have focused their attention on renewable energy sources, in particular, energy storage systems with phase-change materials. These materials in the latent heat devices can be stored in quadrilateral, circular, elliptical, and hexagonal enclosures [1]. The main deficiency of these materials is the low thermal conductivity. As metal nanoparticles have high thermal conductivity and regarding the nanotechnology development, adding nanoparticles to PCMs significantly improved their thermal conductivity [2]. These materials are called NEPCM. In the present study, the non-uniform magnetic fields with positive and negative gradients on the progression of the melting and solidification of the NEPCM in two-dimensional form was investigated numerically. In the present paper homogeneous single phase model is used and the simulations are done by the commercial software of ANSYS FLUENT 16 in the square enclosure. The results of this work have been obtained by analyzing the melting and solidification processes of non-electrical conductivity ferro-fluid by using the enthalpy-porosity method.

2- Governing Equations

In this study, phase change processes of NEPCM are modeled with the enthalpy-porosity method. This method instead of implicitly examining the solid-liquid interface from a value called the liquid fraction, in each cell in the computational region in each iteration based on the enthalpy balance, calculates. The liquid fraction is defined as:

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$$\gamma = \begin{cases} 0 & ;if \quad T < T_{solidus} \\ \dfrac{T - T_{solidus}}{T_{Liquidus} - T_{solidus}} & ;if \quad T_{Liquidus} < T < T_{solidus} \\ 1 & ;if \quad T > T_{Liquidus} \end{cases} \tag{1}$$

The governing equations will be as follows:
Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

Momentum equations:

$$\rho_{nf}\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial P}{\partial x} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \mu_0 M\frac{\partial H}{\partial x} + S_x \tag{3}$$

$$\rho_{nf}\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial P}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \mu_0 M\frac{\partial H}{\partial y} + \rho_{nf}\beta_{nf}\, g\,(T - T_c) + S_y \tag{4}$$

By applying the magnetic field through the external body force, source terms ($\mu_0 M(\partial H/\partial x)$ and $\mu_0 M(\partial H/\partial y)$) caused by the Kelvin force from the ferrohydrodynamics are added to the momentum equations in the directions x and y, respectively.

Also, M, which is magnetization, is given by:

$$M = \frac{6m_p}{\pi d_p^3}\left\{\coth\left(\frac{\mu_0 m_p H}{K_b T}\right) - \frac{K_b T}{\mu_0 m_p H}\right\} \quad (5)$$

Energy equation:

$$(\rho C_p)_{nf}\left(\frac{\partial A}{\partial t} + u\frac{\partial A}{\partial x} + v\frac{\partial A}{\partial y}\right) = k_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu_{nf}\left\{2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right\} \quad (6)$$

3- Thermophysical Properties

Thermophysical properties of homogeneous single phase mixture can be considered as:

Mixture density:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \quad (7)$$

Mixture heat capacity:

$$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_p \quad (8)$$

Mixture viscosity:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \quad (9)$$

Mixture thermal conductivity:

$$k_{nf} = \frac{k_p + (n-1)k_f - (n-1)(k_f - k_p)\phi}{k_p + (n-1)k_f + (k_f - k_p)\phi} k_f \quad (10)$$

Mixture latent heat:

$$(\rho L_h)_{nf} = (1-\phi)(\rho L_h)_f \quad (11)$$

Mixture thermal expansion coefficient:

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_p \quad (12)$$

4- Problem Definition and Numerical Modeling

The effect of non-uniform magnetic field applying (positive and negative gradients) on the melting and solidification process of without electrical conductivity ferrofluid of water and iron oxide nanoparticles in two states of 2% and 5% in a square enclosure has been investigated. It is assumed that the diameter of the nanoparticles is 10 nm, and the gravity is in the down direction of the enclosure.

Also, some assumptions are considered in the numerical solution as follows:

1. The matter is Newtonian and incompressible.
2. The motion of the fluid inside the enclosure is considered as a two-dimensional laminar flow.
3. The fluid viscosity dissipation is negligible.
4. The thermophysical properties of NEPCM are constant except density, as the Boussinesq approximation is considered for calculating the density variations with temperature.
5. The electrical conductivity of ferrofluid is also neglected.
6. Brownian motions and thermophoresis of nanoparticles are not considered.

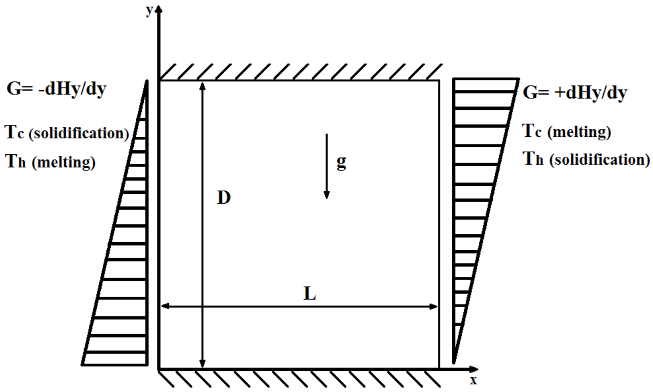

Fig. 1. Schematic of the problem

5- Results and Discussion

The verification of the developed model in this paper is done by comparing the obtained results with a numerical study in which the melting process of water copper nanofluid is considered without magnetic field (See Fig. 2). As the figure shows, there is a good agreement between the two results.

As can be seen, there is a good agreement between the results obtained from the numerical solution based on the Lattice Boltzmann Method and the present numerical solution results. Both in melting and solidification process, the time of this processes in the enclosure is shortened by adding iron oxide nanoparticles with 2% and 5% volume fractions to the PCM. So, with increasing of the volume fraction of nanoparticles, this time becomes less. In the solidification process by applying magnetic field with positive and negative gradients with a magnitude of $\pm 4.4\times10^4$ (A/m^2) and $\pm 2.0\times10^5$ (A/m^2) in y direction and in the same volume fractions, the process takes place faster which in the negative gradient is faster due to the Kelvin force and the solidification process flow direction in the mushy zone is the same direction. Also, with increasing of magnetic field intensity, the solidification process time is improved. Unlike the solidification process, in the melting process, since with increasing of time the natural flow cover the whole of the entire enclosure, the effect of non-uniform magnetic fields with different intensities is appreciable. In this process, by applying non-uniform magnetic fields with intensities of $\pm 4.4\times10^4$ (A/m^2) and $\pm 2.0\times10^5$ (A/m^2) in y direction, the changes in the progression of the melting front are created in decrease or increase speed of this process. So that in the field intensity of $+4.4\times10^4$ (A/m^2) and in the 2% of volume fraction, the melting process time is increased, in other words, the process speed is reduced, but in other modes, the melting process time decreases. Again in this process, the magnetic field with a negative gradient towards the magnetic field with a positive gradient has a greater effect on the speed of the melting front and its time reduction.

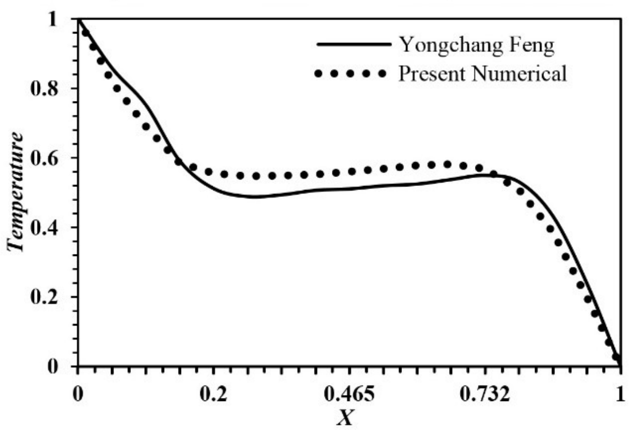

Fig. 2. a comparison of the present model and numerical solution with Lattice Boltzmann Method

6- Conclusion

In this numerical study, the effect of non-uniform magnetic fields on melting and solidification processes was studied for nanofluid of water and iron oxide particles. By adding nanoparticles, phase change processes have been improved. In addition, the applied magnetic field also led into accelerating the melting and solidification processes. By applying magnetic fields to the ferrofluid, changes in the shape of the solidification and melting front reduce and the time of these processes even increase. Since the magnetic field is applied to the mushy zone and in this region either in solidification process or in melting process, flow is downward, so in both processes, a magnetic field with negative gradient caused speed increase in the melting and solidification processes.

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