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Numerical investigation of magnetohydrodynamic forced convection of phase change materials using the lattice Boltzmann method

Mostafa Ahmadi[1], Iman Zahmatkesh[2*], Hamidreza Goshayeshi[2],

[1]PhD Student, Department of Mechanical Engineering, Ma.C., Islamic Azad University, Mashhad, Iran
[2]Professor, Department of Mechanical Engineering, Ma.C., Islamic Azad University, Mashhad, Iran
* imanzahmatkesh@iau.ac.ir

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Abstract

This paper focuses on the numerical simulation and analysis of forced convection heat transfer of a paraffin-alumina nanofluid in a porous channel under an external magnetic field. To this aim, the dimensionless form of the Darcy-Brinkman-Forchheimer equations is solved under local thermal non-equilibrium conditions. The simulations are performed using the thermal lattice Boltzmann method with a single relaxation time scheme, incorporating distribution functions for velocity, nanofluid temperature, and porous medium temperature in an unsteady state condition. In this paper, the effects of parameters such as magnetic field angle, Darcy number, porosity, nanoparticle volume fraction, and Hartmann number on the average Nusselt number, degree of local thermal non-equilibrium, and melting fraction at different time intervals are investigated. The results show that the optimal melting performance occurs at the magnetic field angle of 90°, the Darcy number of 0.001, the porosity of 0.5, the Hartmann number of 30, the nanoparticle volume fraction of 4%, and the Reynolds number of 200, leading to a melting fraction of approximately 88.91% within less than an hour. Conversely, the weakest performance corresponds to the Hartmann number of 50, which increases the required time to reach the melting fraction of 85% to about 198.83 minutes. Furthermore, it is observed that an increase in the average Nusselt number is accompanied by an increased local thermal non-equilibrium.

Keywords: Phase change materials, Porous media, Magnetic field, Local thermal non-equilibrium, Lattice Boltzmann method

1. Introduction

Phase change materials are recognized as a primary approach for thermal energy storage, finding diverse applications across multiple industries due to their capacity to absorb and emit energy during the processes of melting and solidification. These materials function similarly to thermal batteries, utilizing latent heat to store thermal energy and subsequently releasing it upon freezing. Their unique property of heat storage and release during phase transitions facilitates energy generation and temperature control [1]. Datil et al. [2] conducted a comprehensive review of the fundamental principles governing phase change materials, their roles in enhancing energy efficiency, and the associated challenges in their application. They introduced models derived from the first and second laws of thermodynamics to forecast the behavior of these materials. Togan et al. [3] conducted a comprehensive review of different facets of phase change materials, strategies for optimizing their efficacy, and several hybridization methods. Their findings indicated that hybridization techniques have the potential to significantly improve the performance of energy storage systems utilizing phase change materials, while also addressing the economic considerations necessary for the long-term sustainability of these systems.

Choi et al. [4] proposed the concept of distributing nanoparticles, which are smaller than 100 nanometers, within a liquid medium. Their findings indicated that the incorporation of nano-additives into traditional fluids can enhance the heat transfer rate by a factor of two, attributed to the superior thermal conductivity of these nanoparticles. Their study suggests that when nanoparticles are effectively dispersed, it is possible to achieve more stable and thermally conductive systems. Han et al. [5] investigated methods to enhance the thermal stability of phase change materials (PCMs) through the incorporation of nanoparticles, emphasizing their contribution to the efficiency of solar energy storage systems. They introduced a phase change material designed to function as a thermal energy storage unit, aimed at ensuring both stability and adaptability in solar energy-driven heating and cooling applications. Furthermore, they formulated a mathematical model to assess the melting dynamics of PCMs, taking into account the influence of nanoparticles on thermal transfer. The findings indicate that natural convection significantly influences the flow characteristics, particularly in the initial stages of the

PCM melting process, primarily due to buoyancy effects.

Shawai et al. [6] performed both experimental and numerical investigations into the heat transfer properties of phase change materials within porous media. Their findings indicated that the integration of paraffin with metal foam yielded the most effective results, enhancing flow and heat transfer within the pore structure. Meanwhile, Kadhim et al. [7] examined the natural convection of nanofluids in a porous chamber characterized by wavy walls. This research demonstrated that accounting for the local thermal discrepancies between the nanofluid and the porous medium significantly improves the accuracy of heat transfer predictions.

Mabrouk et al. [8] conducted a numerical assessment of how porosity influences forced convection heat transfer within an open-ended horizontal channel containing a porous medium (copper) and a phase change material (paraffin) under conditions of local thermal non-equilibrium. Their findings indicated that smaller porosities enhance the melting rate of the phase change material. In a separate study, Parhizi et al. [9] examined the flow dynamics and heat transfer characteristics in a porous channel with walls maintained at a constant flux, employing a local thermal non-equilibrium framework.

The study of fluid dynamics and thermal exchange influenced by an external magnetic field is referred to as magnetohydrodynamics. A comprehensive review of existing literature indicates that the magnetohydrodynamic convection of nanofluids within porous media has been extensively examined. Fekur et al. [10] explored the dynamics of flow and heat transfer in a porous channel characterized by permeable walls under the influence of a magnetic field. Their findings revealed that an increase in the Hartmann number leads to a reduction in the velocity of the nanofluid while simultaneously elevating its temperature.

The lattice Boltzmann method serves as a technique for simulating fluid dynamics and thermal transfer. Feng et al. [11] employed this method to model convective heat transfer within a porous medium, revealing that a reduction in the Darcy number correlates with a decrease in the value of . Moradi et al. [12] explored the impact of porosity on flow dynamics in a porous medium through the lattice Boltzmann method. Their findings indicated that, while maintaining a constant porosity, variations in pore quantity or configuration significantly influence the velocity and temperature distributions, as well as the Nusselt number.

2. Problem's physics

The issue being examined, illustrated in Figure 1, involves a two-dimensional channel with two open ends that is filled with paraffin-alumina nanofluid and incorporates a metallic porous structure. This porous structure is characterized by a series of circular apertures with a diameter denoted as dp. The channel's dimensions are represented by the symbols L for length and H for height. It is assumed that the channel walls maintain a constant temperature, are impermeable, and exhibit no-slip conditions. A stream of hot air, maintained at a constant temperature Th and an initial uniform velocity U_0, enters the channel, triggering the melting of the paraffin; subsequently, the flow exits the channel's right side at a temperature Tc. The flow at the outlet is considered to be fully developed. Furthermore, the Reynolds number is constrained within the range of $200 \leq Re \leq 400$. The governing equations are predicated on several assumptions: the flow is unsteady, laminar, incompressible forced convection with negligible viscous losses. Additionally, natural convection heat transfer and radiation exchange are disregarded. It is also noted that local thermal non-equilibrium conditions prevail between the solid and fluid phases, while the thermophysical properties of the porous material (copper) and the paraffin with alumina nanoparticles are treated as constant

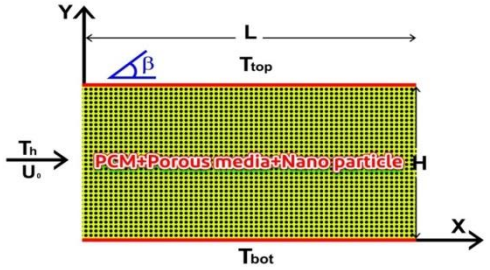

Figure 1. Schematic view of the physical model

3. Macroscopic equations

According to the above assumptions, the macroscopic governing equations can be written as follows [8].

$$\nabla.\vec{V} = 0 \tag{1}$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}.\nabla)(\varepsilon^{-1}\vec{V}) = -\nabla(\varepsilon P) + \nu_{nf}\nabla^2\vec{V} + \varepsilon\vec{F} \tag{2}$$

$$\varepsilon(\rho C_p)_{nf}\left(\frac{\partial T_{nf}}{\partial t} + \vec{V}.\nabla T_{nf}\right) = \nabla.(k_{nf}\nabla T_{nf}) + h_{sf}a_{sf}(T_s - T_{nf}) - \varepsilon\rho_{nf}L_a\frac{\partial \Gamma}{\partial t} \tag{3}$$

$$(1-\varepsilon)(\rho C_p)_s\frac{\partial T_s}{\partial t} = \nabla.(k_{eff,s}\nabla T_s) + h_{sf}a_{sf}(T_f - T_s) \tag{4}$$

Using dimensionless variables, equations 1 to 4 are dimensionless as follows:

$$\nabla.\vec{U} = 0 \tag{5}$$

$$\frac{\partial \vec{U}}{\partial \tilde{t}} + (\vec{U}.\nabla)(\varepsilon^{-1}\vec{U}) = -\nabla(\varepsilon P) + \tag{6}$$

$$\frac{1}{\mathrm{Re}}\nabla^2\vec{U}+\varepsilon\vec{\tilde{F}}$$

$$\frac{\partial\Theta_{nf}}{\partial\tilde{t}}+\vec{U}.\nabla\Theta_{nf}=\frac{1}{\varepsilon \mathrm{Re}\,\mathrm{Pr}}\nabla.\left(\frac{k_{eff.nf}}{k_{nf}}\nabla\Theta_{nf}\right)+\frac{k_r\,\mathrm{Bi}}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\Theta_s-\Theta_{nf}}{\varepsilon}\right)-\frac{1}{\mathrm{Ste}}\frac{\partial\tilde{\Gamma}}{\partial\tilde{t}} \quad (7)$$

$$\frac{\partial\Theta_s}{\partial\tilde{t}}=\frac{k_r}{Rc}.\frac{1}{\mathrm{Re}.\mathrm{Pr}}\nabla.\left(\frac{k_{eff,s}}{k_s}\nabla\left(\frac{\Theta_s}{1-\varepsilon}\right)\right)-\frac{k_r}{Rc}.\frac{\mathrm{Bi}}{\mathrm{Re}.\,\mathrm{Pr}}\left(\frac{\Theta_s-\Theta_{nf}}{1-\varepsilon}\right) \quad (8)$$

4. Lattice Boltzmann equations

In the lattice Boltzmann method, the density distribution function and two temperature distribution functions ($g_{i_{f,s}}$) are expressed as follows to obtain the temperature field of the fluid and porous material [8]:

$$f_i(\vec{x}+\vec{e}_i\delta t,t+\delta t)-f_i(\vec{x},t)=-\omega_i\left[f_i(\vec{x},t)-f_i^{eq}(\vec{x},t)\right]+\delta t F_i \quad (9)$$

$$g_{nf,i}(\vec{x}+\vec{e}_i\delta t,t+\delta t)-g_{nf,i}(\vec{x},t)=-\omega_{T,nf}\left(g_{nf,i}(\vec{x},t)-g_{nf,i}^{eq}(\vec{x},t)\right)+(1+\frac{\delta t\,\partial_t}{2})\delta t Sr_{i,nf} \quad (10)$$

$$g_{s,i}(\vec{x}+\vec{e}_i\delta t,t+\delta t)-g_{s,i}(\vec{x},t)=-\omega_{T,s}\left(g_{s,i}(\vec{x},t)-g_{s,i}^{eq}(\vec{x},t)\right)+(1+\frac{\delta t\,\partial_t}{2})\delta t Sr_{i,s} \quad (11)$$

Utilizing the principles of mass conservation and momentum conservation at each junction within the network, the macroscopic density and velocity can be derived from the following equations, respectively:

$$\rho_{nf}=\sum_i f_i \quad (12)$$

$$\vec{V}=\frac{\sum_i f_i\vec{e}_i}{\rho_{nf}}+\frac{\delta t\vec{E}}{2} \quad (13)$$

Finally, the macroscopic temperatures of the fluid and solid and the expressions $Sr_{i,s}$ and $Sr_{i,nf}$ are defined as follows, respectively [8]:

$$T_{nf}=\sum_{i=0}^{8} g_{nf,i} \quad (14)$$

$$T_s=\sum_{i=0}^{8} g_{s,i} \quad (15)$$

$$Sr_{i,nf}=w_i\left(La(\frac{\gamma(t+\delta t)-\gamma(t)}{\delta t})/C_{p,nf}+h(T_s-T_{nf})/(\varepsilon(\rho C_p)_{nf})\right) \quad (16)$$

$$Sr_{i,s}=w_i\left(\frac{h(T_s-T_{nf})}{(1-\varepsilon)(\rho C_p)_s}\right) \quad (17)$$

5. Results and discussions

A primary aim of this research was to examine the average Nusselt number and local thermal imbalance in relation to several factors, including the angles of the magnetic field, Darcy number, porosity coefficient, nanoparticle volume fraction, and Hartmann number. While the influence of these factors has been discussed in earlier sections, this section focuses on the analysis presented in Table 1, which details the maximum average Nusselt number and local thermal imbalance across the different variables.

Table 1. Maximum average Nusselt number and local thermal non-equilibrium for different variables

Variable	State	Average Nusselt number	Local thermal non-equilibrium
Field angle	90^0	6.1877	0.07632
Darcy number	0.01	6.2595	0.08127
Porosity coefficient	0.5	6.4007	0.09599
Volume fraction	%6	6.5506	0.07650
Hartmann number	50	6.3327	0.08775

Another goal of this paper was to investigate the melting fraction percentage for different variables. To do this, first the highest melting percentage in the best case of the variable under study and the time to reach this melting fraction are given. Table 2 shows the results of this study.

Table 2. Maximum melting percentage for different variables

Variable	State	Time (min)	Melting fraction (%)
Field angle	90^0	93.13	86.304
Darcy number	0.01	167.16	84.143
Porosity coefficient	0.5	58.36	88.91
Volume fraction	%6	196.66	88.78
Hartmann number	50	198.83	84.697

6. Conclusions

In this paper, a numerical evaluation of a non-equilibrium model in simulating the forced convection of paraffin-alumina nanofluid in a horizontal channel filled with porous material in the presence of a magnetic field was presented. For this purpose, the

lattice Boltzmann method was used. Subsequently, the effect of effective variables including magnetic field angle, Darcy number, porosity coefficient, volume fraction of nanoparticles and Hartmann number on the average Nusselt number, local thermal non-equilibrium amount, melting fraction percentage and melting time was studied. Based on the presented results, the following conclusions were obtained:

(1) With a porosity of 0.5, a melting fraction of 88.91 can be reached in less than an hour.
(2) The minimum time required to reach a melting fraction of over 88% is 58 minutes.
(3) The best case to reach a melting percentage of over 85 in the shortest possible time is to use a minimum porosity.
(4) The worst case is to use Hartmann 50 to reach a melting fraction of 85% in 198.83 minutes.
(5) The amount of local thermal non-equilibrium changes proportionally to the average Nusselt number.
(6) The best case to reach a melting fraction of 84% in the shortest possible time is: angle 90 degrees, Darcy number 0.001, porosity 0.5, Hartmann number 30, volume fraction 4% and Reynolds number 200.

7. References

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