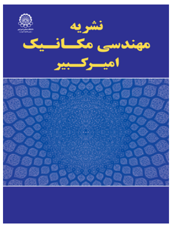

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 54(5) (2022) 241-244
DOI: 10.22060/mej.2022.20401.7226

Investigation of 2D Melting Process within a Porous Medium Considering Local Thermal Nonequilibrium Condition in the Presence of Sinusoidal Boundary Condition by Lattice Boltzmann Method

M. Taghilou, S. A. Safavi

Department of Engineering, University of Zanjan, Zanjan, Iran.

ABSTRACT: This paper investigates the local temperature difference between the phase change material and porous medium during the two-dimensional melting process by considering natural convection and applying sinusoidal boundary condition. Hence, the density distribution function is used to solve momentum equations and two separate distribution functions are used to solve energy equations to calculate the local temperature difference and liquid fraction of the phase change material. Also, the effect of parameters such as amplitude and frequency of oscillation and Sparrow number on the percentage of local temperature difference and comparison of liquid fraction in the presence and absence of natural convection, are studied. Results show that with increasing frequency from 1 to 3, the percentage of local temperature difference increased from 41.44% to 67.53%, and with increasing oscillation amplitude from 1 to 3, the percentage of local temperature difference is reduced from 41.44% to 20.56%. Also, by increasing the Sparrow number from 322 to 6000, the percentage of local temperature difference decreases from 41.44% to 4.21%. Also, it is observed that by changing oscillation frequency, liquid fraction does not change much compared to the conditions of pure conduction; however, as the amplitude of oscillation increases, the percentage of deviation of liquid fraction from the pure conduction increases.

Review History:

Received: Aug. 13, 2021
Revised: Jan. 09, 2022
Accepted: Feb. 17, 2022
Available Online: Feb. 17, 2022

Keywords:

Melting process
Porous medium
Local temperature difference
Sinusoidal boundary temperature
Lattice Boltzmann method

1- Introduction

In the present paper, the process of simultaneous melting and solidification within a square porous medium with sinusoidal boundary condition is investigated. The existence of oscillation in the temperature field and also a large difference between the conductivity coefficients of the phase change material and the porous medium, has made it necessary to apply the local thermal nonequilibrium condition [1-3]. Also, considering the effect of natural convection in the process of phase change and the development of analytical models in the pure conduction conditions, it is one of the objectives of this article to investigate the necessary conditions to ignore the effects of natural convection. Accordingly, the enthalpy method based on the Boltzmann equation has been used to solve the momentum and energy equations. Numerical results show the effect of parameters such as frequency and amplitude of boundary oscillation and Sparrow number on the local temperature difference between the phase change material and the porous medium as well as the difference of liquid fraction in the presence and absence of natural convection.

2- Problem Definition

The geometry of the problem is a square enclosure with dimensions of 150×150, which is completely filled by the porous medium as shown in Fig. 1. The boundary condition for the upper and lower wall is insulation and the boundary condition for the left and right wall is considered as a specific temperature with oscillating values according to Eq. (1).

$$T_w^* = \frac{-A\,T_m}{T_{in} - T_m} sin\left(2\,\pi fFo\right) \tag{1}$$

3- Governing Equations

Due to the presence of the local thermal nonequilibrium condition, it is necessary to solve two energy equations, one for the phase change material (liquid phase) and the other for the porous medium (solid phase). Macroscopic equations of energy for phase change material and porous medium are expressed by Eqs. (2) and (3), respectively [4]:

$$\varepsilon \frac{\partial En_f}{\partial t} + \nabla.\left[\left(\rho c_p\right)_{fl} \mathbf{u} T_f\right] = k_{e,f} \nabla^2 T_f + h_v\left(T_s - T_f\right) \tag{2}$$

$$\left(1-\varepsilon\right)\frac{\partial En_s}{\partial t} = k_{e,s} \nabla^2 T_s + h_v\left(T_f - T_s\right) \tag{3}$$

*Corresponding author's email: taghilou@znu.ac.ir

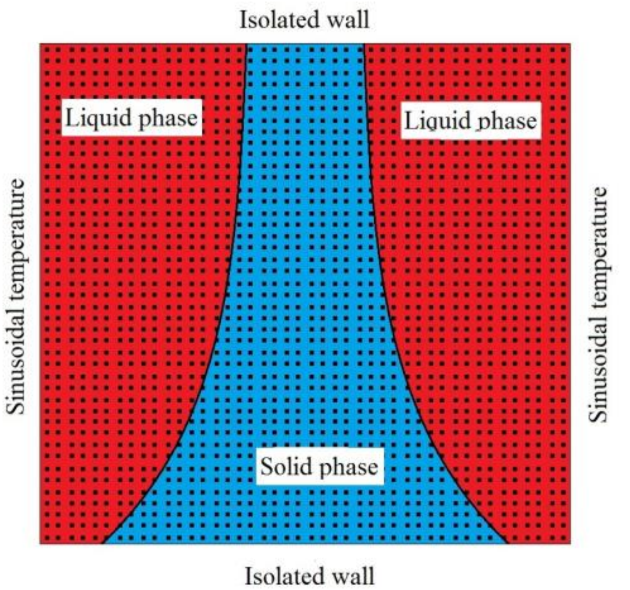

Fig. 1. Schematic of the melting problem with sinusoidal boundary condition.

where u, T, and c_p, show the velocity field, temperature, and specific heat capacity, respectively. Also, En_f is the total enthalpy for phase change material, En_s expresses the total enthalpy for porous medium, ε is the porosity of the medium, k_e is the effective conductivity and h_v is the convective coefficient between the porous medium and the liquid phase of the phase change material per unit volume. In Eqs. (2) and (3), the indices of f, s, and fl indicate the phase change material, the porous medium, and the liquid phase of the phase change material.

Mass and momentum conservation equations are written on a macroscopic scale for a porous medium according to Eqs. (4) and (5) [4]:

$$\nabla.\mathbf{u} = 0 \tag{4}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)(\frac{\mathbf{u}}{\varepsilon}) = -\frac{1}{\rho_{fl}}\nabla(\varepsilon p) + \upsilon\nabla^2\mathbf{u} + \mathbf{F} \tag{5}$$

In Eqs. (4) and (5), p and v are pressure and kinematic viscosity, respectively. **F** represents the total volumetric forces created by the porous medium and other external forces.

The non-dimensional numbers controlling the fluid flow problem along with the heat transfer and the phase change phenomenon are: Prandtl number Pr, Rayleigh number Ra, Darcy number Da, Stephen number Ste, Nusselt number Nu_d and the porosity ε which are defined by:

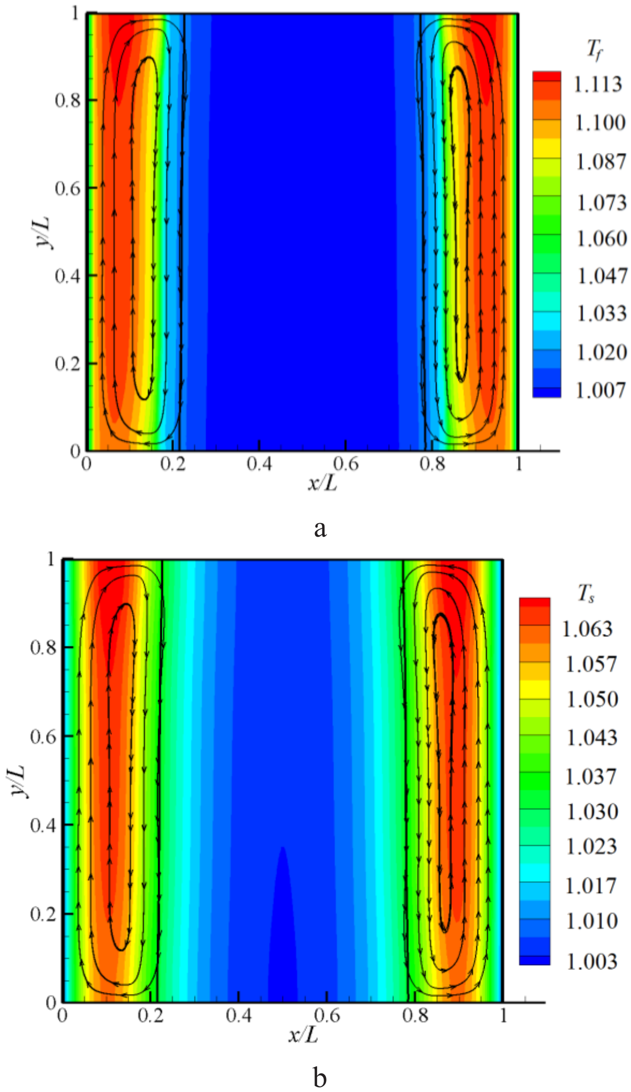

Fig. 2. Nondimensional temperature contours and streamlines along with the melting front position for the base state, a) phase change material b) porous medium

$$\begin{aligned}&\mathrm{Pr} = \frac{\upsilon}{\alpha_{fl}}, \mathrm{Ra} = \frac{g\beta\Delta T L^3}{\upsilon\alpha_{fl}}, \mathrm{Da} = \frac{K}{L^2}, \mathrm{Ste} = \frac{c_{p,f}\Delta T}{L_a} \\ &\mathrm{Nu_d} = \frac{h_v d_p^2}{k_l}, \varepsilon = \frac{V_{empty}}{V_{total}}, T^* = \frac{T - T_{in}}{T_m - T_{in}}, \mathrm{Fo} = \frac{\alpha_f t}{L^2}\end{aligned} \tag{6}$$

The dimensionless number that controls the local thermal nonequilibrium condition is the Sparrow number. The Sparrow number and the equivalent thermal conductivity of the porous medium are defined according to Eqs. (7) and (8), respectively [1]:

$$\mathrm{Sp} = \frac{h_v L^3}{k_e r_h} \tag{7}$$

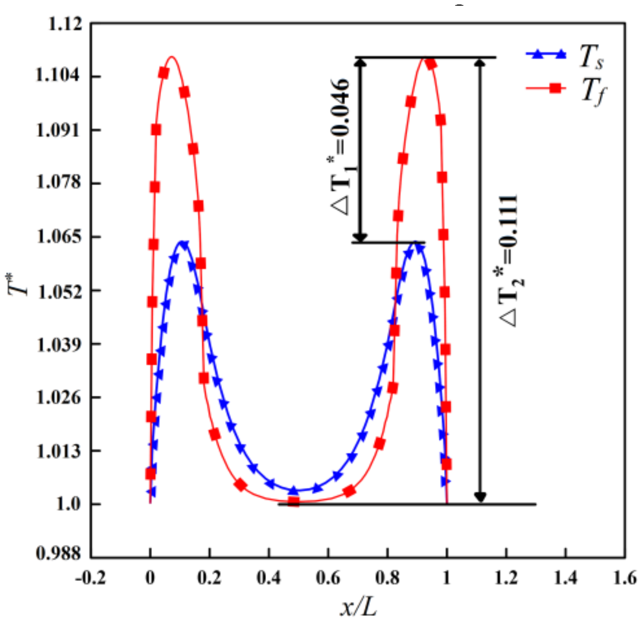

Fig. 3. Temperature distribution of phase change material and porous medium for the base conditions, f=1, A = 1, and Sp = 322.

$$k_e = \varepsilon k_f + (1-\varepsilon) k_s \quad (8)$$

The macroscopic equations are solved by the lattice Boltzmann method [4].

4- Results and Discussion

After ensuring the accuracy of numerical modeling, the results are reported. Fig. 2 shows the temperature field of the phase change material and the porous medium along with the streamlines and the position of the melting front at Fo=0.002 and Sp=322, which is in accordance with the base conditions.

Fig. 3 shows the dimensionless temperature distribution of the phase change material and the porous medium in the middle position of the enclosure for the base state. For the base case, the percentage of local temperature difference is equal to 41.44%.

5- Conclusion

1- As the frequency of oscillation increases, the percentage of local temperature difference increases, so that with increasing the frequency from 1 to 3 the percentage of local temperature difference increases from 41.44% to 67.53%.

2- Numerical results show that with increasing the amplitude of dimensionless oscillation from 1 to 3, the percentage of local temperature difference decreases from 41.41% to 20.56%. Therefore, by increasing the amplitude of the boundary temperature oscillation, the necessity of applying the local thermal nonequilibrium is reduced. As the amplitude of the oscillation increases, the position of the melting front also becomes curved and becomes flat, which indicates an increase in the effects of natural convection.

3- Oscillation frequency has little effect on the liquid fraction of the phase change material so that the maximum value of this deviation is equal to 0.58%.

References

[1] W. Minkowycz, A. Haji-Sheikh, K. Vafai, On departure from local thermal equilibrium in porous media due to a rapidly changing heat source: the Sparrow number, International journal of heat and mass transfer, 42(18) (1999) 3373-3385.

[2] A. Nakayama, F. Kuwahara, M. Sugiyama, G. Xu, A two-energy equation model for conduction and convection in porous media, International journal of heat and mass transfer, 44(22) (2001) 4375-4379.

[3] X. Zhang, G. Su, J. Lin, A. Liu, C. Wang, Y. Zhuang, Three-dimensional numerical investigation on melting performance of phase change material composited with copper foam in local thermal non-equilibrium containing an internal heater, International Journal of Heat and Mass Transfer, 170 (2021) 121021.

[4] D. Gao, F.-B. Tian, Z. Chen, D. Zhang, An improved lattice Boltzmann method for solid-liquid phase change in porous media under local thermal non-equilibrium conditions, International Journal of Heat and Mass Transfer, 110 (2017) 58-62.

HOW TO CITE THIS ARTICLE

M. Taghilou, S. A. Safavi, Investigation of 2D Melting Process within a Porous Medium Considering Local Thermal Nonequilibrium Condition in the Presence of Sinusoidal Boundary Condition by Lattice Boltzmann Method , Amirkabir J. Mech Eng., 54(5) (2022) 241-244.

DOI: 10.22060/mej.2022.20401.7226