Effect of dispersing nanoparticles on solidification process in existence of Lorenz forces in a permeable media

Zhixiong Li a,b, M. Sheikholeslami c,⁎, Ahmad Shafee d, S. Saleem e, Ali J. Chamkha f,g

a School of Engineering, Ocean University of China, Qingdao 266101, China
b School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
c Department of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Islamic Republic of Iran
d Public Authority of Applied Education & Training, College of Technological Studies, Applied Science Department, Shuwaikh, Kuwait
e Department of Mathematics, College of Science, King Khalid University, Abha 61413, Saudi Arabia
f Mechanical Engineering Department, Prince Sultan Endowment for Energy and Environment, Prince Mohammad Bin Fahd University, Al-Khobar 31952, Saudi Arabia
g RAK Research and Innovation Center, American University of Ras Al Khaimah, United Arab Emirates

Abstract

In current article, Lorentz forces in influence on NEPCM solidification phenomena in a storage porous unit is reported with numerical method via FEM. Nanotechnology and magnetic field are employed to expedite this unsteady process. Roles of Hartmann number, Rayleigh number and volume fraction of NEPCM have been reported. Outputs reveal that solid fraction rises in presence of Lorentz forces. Full discharging time reduces with augment of volume fraction of CuO-water and Hartmann number.

© 2018 Elsevier B.V. All rights reserved.

Keywords:
Phase change material
Finite element method
Magnetic field
Nanoparticle
Porous media
Solidification

1. Introduction

To supply needing of storing heat transfer, thermal energy storage becomes more popular in recent years. Charging and discharging process of PCM have been investigated. Also, researchers used nanoparticles to overcome the limitation of pure PCM. Shahzad et al. [1] employed Buongiorno model to simulate nanofluid migration in a duct. Sheikholeslami et al. [2] demonstrated the acceleration of discharging phenomenon by means of nanoparticles. They added the impact of thermal radiation in governing equations. Mahajan and Sharma [3] illustrated the migration of nanofluid in a permeable cavity in existence of internal heating. Ullah et al. [4] investigated the impact of Newtonian heating on Casson fluid behavior in presence of MHD over a porous sheet. Haq et al. [5] investigated inclined Lorentz forces on nanoparticles movement on a moving plate.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KKL</td>
<td>Koo–Kleinstreuer–Li</td>
</tr>
<tr>
<td>K</td>
<td>Permeability</td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamic</td>
</tr>
<tr>
<td>NEPCM</td>
<td>Nano-Enhanced PCM</td>
</tr>
<tr>
<td>(l_f)</td>
<td>Latent heat coefficient</td>
</tr>
<tr>
<td>(k)</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>PCM</td>
<td>Phase change material</td>
</tr>
</tbody>
</table>

Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>Thermal diffusivity ([m^2/s])</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Fluid density</td>
</tr>
<tr>
<td>(\phi)</td>
<td>Nanoparticle volume fraction</td>
</tr>
</tbody>
</table>

Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f)</td>
<td>Base fluid</td>
</tr>
<tr>
<td>(p)</td>
<td>Particle</td>
</tr>
<tr>
<td>(nf)</td>
<td>Nanofluid</td>
</tr>
</tbody>
</table>

In current article, impact of dispersing nanoparticles on solidification rate is demonstrated considering magnetic field impact. This transient process has been modeled by FEM. Roles of nanoparticles volume fraction, Lorentz and buoyancy forces on solidification process were illustrated in graphs.

2. Problem explanation

Fig. 1 presents the porous storage unit. Table 1 shows the nanoparticles and pure PCM properties. Uniform magnetic field was employed to control the solidification rate of NEPCM.

3. Problem formulation

Influence of Lorentz forces on NEPCM solidification is taken into account in governing formula:

\[
\nabla \cdot \bar{V} = 0
\]

(1)

\[
(\bar{T} \times \bar{B} - \nabla p + \rho_{nf} \bar{\sigma}_{nf}) = \frac{\mu_{nf}}{\kappa} \bar{V}
\]

(2)

\[
(\rho C_p)_{nf} \frac{d\bar{T}}{dt} = \nabla (k_{nf} \nabla \bar{T}) + L_{nf} \frac{dS}{dt}
\]

(3)

\[
\begin{align*}
S = 0 & \quad & T > (T_m + T_0) \\
S = 1 & \quad & T < (T_m + T_0) \\
S = (0.5T_0 + T_m) + T_0 & \quad & T < (T_m + T_0) \\
\end{align*}
\]

(4)

\[
(\nabla \times \bar{B} - \nabla \omega) \sigma_{nf} = \bar{T},
\]

\[
\nabla \cdot \bar{T} = 0
\]

(5)

According to above equations, final formulas are:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

(6)

\[
u + \frac{K \partial p}{\mu_{nf} \partial x} = \sin^2 \gamma \frac{K \sigma_{nf} B_0^2}{\mu_{nf}} (v \tan \gamma - u)
\]

(7)

\[
\frac{\sigma_{nf} K B_0^2}{\mu_{nf}} \cos^2 \gamma (v + u \tan \gamma) + g \frac{K}{\mu_{nf}} (\rho f \tan \gamma) = v + \frac{K \partial p}{\mu_{nf} \partial y}
\]

(8)

\[
\frac{d\bar{T}}{dt} = \frac{k_{nf}}{(\rho C_p)_{nf}} \nabla (\nabla \bar{T}) + \frac{L_{nf}}{(\rho C_p)_{nf}} \frac{dS}{dt}
\]

(9)

\[
\begin{align*}
S = 0 & \quad & T > (T_m + T_0) \\
S = 1 & \quad & T < (T_m + T_0) \\
S = (0.5T_0 - T_m) + T_0 & \quad & T < (T_m + T_0) \\
\end{align*}
\]

(10)

Table 1

The physical properties of water as PCM, CuO as nanoparticles.

<table>
<thead>
<tr>
<th>Property</th>
<th>PCM</th>
<th>Nanoparticles</th>
<th>Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho) ([kg/m^3])</td>
<td>997</td>
<td>6500</td>
<td>917</td>
</tr>
<tr>
<td>(C_p) ([J/kgK])</td>
<td>4179</td>
<td>540</td>
<td>2040</td>
</tr>
<tr>
<td>(k) ([W/mK])</td>
<td>0.6</td>
<td>18</td>
<td>2.21</td>
</tr>
<tr>
<td>(L_f) ([J/kg])</td>
<td>335,000</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2

The coefficient values of CuO – Water nanofluid.

<table>
<thead>
<tr>
<th>Coefficient values</th>
<th>CuO – Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_1)</td>
<td>–26.5933110846</td>
</tr>
<tr>
<td>(a_2)</td>
<td>–0.403818333</td>
</tr>
<tr>
<td>(a_3)</td>
<td>–33.3516805</td>
</tr>
<tr>
<td>(a_4)</td>
<td>–1.915825591</td>
</tr>
<tr>
<td>(a_5)</td>
<td>6.42185846558E–02</td>
</tr>
<tr>
<td>(a_6)</td>
<td>48.4033695</td>
</tr>
<tr>
<td>(a_7)</td>
<td>–9.787756683</td>
</tr>
<tr>
<td>(a_8)</td>
<td>190.245610009</td>
</tr>
<tr>
<td>(a_9)</td>
<td>10.92835856</td>
</tr>
<tr>
<td>(a_{10})</td>
<td>–0.72009983664</td>
</tr>
</tbody>
</table>
\((\rho C_p)_{nf}, \rho_{nf}, (\rho \beta)_n, \sigma_{nf}\) and \((\rho L)_{nf}\) can be obtained as:

\[
\frac{(\rho C_p)_{nf}}{C_0/C_1} = \frac{\rho_{nf}}{\phi \rho + \rho_f (1-\phi)} + \frac{(\rho \beta)_n \phi (1-\phi) (\rho \beta)_f}{\phi \rho + \rho_f (1-\phi)}
\]

\[
\rho_{nf} = \phi \rho + \rho_f (1-\phi)
\]

\[
(\beta)_n = (\beta)_n \phi (1-\phi) (\beta)_f
\]

\[
\sigma_{nf} - 1 = -3 \left(1 - \frac{\sigma_s}{\sigma_f} \right) \phi + \left(2 + \frac{\sigma_s}{\sigma_f} \right)
\]

\[
(\rho L)_{nf} = (1-\phi) (\rho L)_f
\]

\(k_{nf}\) and \(\mu_{nf}\) are [26]:

\[
k_{nf} = \frac{k_f}{1 + 5 \times 10^4 \rho_f \phi \sqrt{\frac{\nu_f}{\nu_f + \rho_f C_p f}}} \left[\frac{g'(d_p, T, \phi)}{d_p \phi} \right] \left(1 - \frac{k_p}{k_f} \right) \phi - \frac{k_p}{k_f - 1} + \frac{k_p}{k_f + 2}
\]

\[
4 \times 10^{-8} / d_p + 1 / k_p = 1 / k_{nf}
\]

\[
g'(d_p, T, \phi) = \left(a_6 + a_8 \ln(d_p) + a_10 \ln(d_p)^2 + a_1 \ln(d_p) + a_9 \ln(d_p) \ln(\phi) + \ln(T) \right) \left(a_2 \ln(d_p) + a_7 \ln(d_p)^2 + a_3 \ln(d_p) + a_4 \ln(d_p) \ln(\phi) \right)
\]

\[
\mu_{nf} = \mu_{static} + \mu_{Brownian} = \mu_{static} + \frac{k_{Brownian}}{k_f} \times \frac{\mu_f}{\eta f}
\]

The needed parameters are illustrated in Table 2.

To eliminate pressure terms, following definitions are used:

\[
\frac{\partial \psi}{\partial x} = v, \frac{\partial \psi}{\partial y} = u
\]

Fig. 3. Validation of current code with comparison with previous experimental work [45].

Non-dimension variables are:

\[
Ra = \frac{\Delta TK L g}{\alpha_{f} \mu_f}, Ha = \frac{\alpha_{f} K B_2^2}{\mu_f}
\]

\(E_{total}\) and \(T_{ave}\) can be obtained as:

\[
E_{total} = \int \left( s (\rho L)_{nf} + (\rho C_p)_{nf} T \right) dV
\]

Fig. 2. Grid refinement procedure when \(\phi = 0.04, Ra = 50, Ha = 0\).
Heat penetration depthness is enhanced with rise of Hartmann number. As Hartmann number augments, solidification enhances. The most uniform discharging process was observed for highest $\phi$, $Ha$. This observation is clear from related diagrams and contour. Full solidification time augments with rise of $Ra$.

Figs. 12 and 13 illustrate $S_{ave}$, $T_{ave}$ for different $Ra$ and $Ha$. Maximum values of $T_{ave}$ occur at beginning of process. As Hartmann number augments, solid fraction enhances. Full discharging time reduces with rise of Hartmann number. As $Ha$ increases, solidification front moves faster than before. Also Fig. 14 proves that Rayleigh number has direct relationship with solidification time.

6. Conclusion

In this research, NEPCM and magnetic field are employed to improve the efficiency of solidification in a thermal storage unit. Roles Hartmann, Rayleigh numbers and NEPCM volume fraction are examined via FEM. Graphs reveal that adding nanoparticles leads to augment solidification rate. $Ra$ has inverse relationship with solidification rate. Employing Lorentz forces can help the PCM solidification.

Acknowledgements

This paper has been supported by the National Natural Science Foundation of China (NSFC) (No. U1610109), Yingcai Project of CUMT (YC2017001), PAPD and UOW Vice-Chancellor’s Postdoctoral Research Fellowship. Also, authors would like to express their gratitude to King Khalid University, Abha 61413, Saudi Arabia for providing administrative and technical support.

\[ T_{ave} = \frac{\int T \, dA}{\int dA} \] (21)

4. FEM and validation

The Galerkin FEM has been chosen to model the transient heat transfer during discharging phenomenon. Temperature and solid fraction are calculated on the nodes which are located on the corners of cell. The final calculations can be solved by the Newton-Raphson method. This method solves the unsteady terms of equations by an implicit backward difference approach. The solidification process is simulated by utilizing the adaptive mesh as depicted in Fig. 2. The current code is verified by comparing the results with previous study [45]. It can be concluded from Fig. 3 shows that an excellent agreement.

5. Results and discussion

In current article, influence of magnetic forces on solidification in a porous thermal storage unit is illustrated. Using nanoparticles and magnetic field are two ways which are selected to expedite discharging process. Influences of nanofluid volume fraction ($\phi = 0$ to 0.04), Hartmann number ($Ha = 0$ to 10) and Rayleigh number ($Ra = 10$ to 100) on rate of solidification are examined by means of FEM.

Figs. 4 and 5 demonstrate the impact of adding nanoparticles in to pure H$_2$O on solidification. As depicted in this figure, adding CuO nanoparticles helps solidification process. Furthermore, as time progresses the influence of $\phi$ become more effective.

Influences of $Ra$ and $Ha$ on NEPCM solidification in various time steps are illustrated in Figs. 6, 7, 8, 9, 10 and 11. As Hartmann number augments, solidification process was finished in shorter time. Heat penetration deepness is enhanced with rise of $Ha$, which can reduce the solidification time. Augmenting buoyancy forces make the rate of solidification to reduce. In absence of magnetic field, there is one rotating eddy in streamline which is shift to upper side as time progresses. This observation is more sensible at greater $Ra$.

The main cell converts to two weaker cells in presence of Lorentz forces.

Figs. 12 and 13 illustrate $S_{ave}$, $T_{ave}$ for different $Ra$ and $Ha$. Maximum values of $T_{ave}$ occur at beginning of process. As Hartmann number augments, solidification enhances. The most uniform discharging process was observed for highest $\phi$, $Ha$. This observation is clear from related diagrams and contour. Full solidification time augments with rise of $Ra$.

Fig. 14 illustrates the impact of $Ra$ and $Ha$ on $Time$. The below correlation can be derived:

\[ Time = 10.11 + 0.37Ra - 0.3(Ra)(Ha) - 4.6 \times 10^{-4}(Ra^2) \] (22)

Full discharging time reduces with rise of Hartmann number. As $Ha$ increases, solidification front moves faster than before. Also Fig. 14 proves that Rayleigh number has direct relationship with solidification time.

\[ \frac{T_{ave}}{Ra} = \frac{\int T \, dA}{\int dA} \]
Fig. 6. Solid fraction, temperature and streamline contour at three different time steps when $\phi = 0.04$, $Ra = 10$, $Ha = 0$. 
Fig. 7. Solid fraction, temperature and streamline contour at three different time steps when $\phi = 0.04$, $Ra = 10$, $Ha = 10$. 

Fig. 8. Solid fraction, temperature and streamline contour at three different time steps when $\phi = 0.04$, $Ra = 50$, $Ha = 0$. 

Fig. 9. Solid fraction, temperature and streamline contour at three different time steps when $\phi = 0.04$, $Ra = 50$, $Ha = 10$. 
Fig. 10. Solid fraction, temperature and streamline contour at three different time steps when $\phi = 0.04$, $Ra = 100$, $Ha = 0$. 
Fig. 11. Solid fraction, temperature and streamline contour at three different time steps when $\phi = 0.04$, $Ra = 100$, $Ha = 10$. 
Fig. 12. Average temperature variations over computational domain during solidification process when $\phi = 0.04$.

Fig. 13. Solid fraction variations during solidification process when $\phi = 0.04$. 
References


Fig. 14. Full solidification time for different values Ra, Ha.