World Applied Sciences Journal 18 (2): 208-213, 2012
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2012.18.02.500

Two-Temperature Model for Improvement of Heat Transport in PCMs Using Porous Matrix

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Abstract: In this paper the effects of, utilization of high thermal conductivity porous matrix on phase change material melting has been numerically studied. The convective motion of liquid phase change material in porous domain is investigated. The convection motion of the liquid phase inside the porous matrix is solved considering the Darcy, Brinkman and Forchiemer effects. A local thermal non-equilibrium assumption is considered due to the large differences in thermal properties between the solid matrix and PCM. The model is based on volume averaged transport, while phase change is assumed to occur over a small temperature range. Influence of porosity, thermal conductivity, pore diameter, hot wall temperature and aspect ratio on phase change material melting is studied. Although the convection motion damps when the porosity of the matrix is decreased but due to the high viscosity, low thermal expansion coefficient of phase change material and high effective thermal conductivity of the total system, the melting rate significantly improves.

Key words: Phase change material · Porous matrix · Thermal conductivity · Two-temperature model · Energy storage

INTRODUCTION

Thermal energy storage (TES) is a useful tool to increase energy efficiency and energy savings. One of the options for this is phase change materials (PCMs). High latent of fusion, high specific heat and small volume change during phase change make PCMs attractive in thermal management of thermal energy storage. The latent heat of phase change materials (PCMs) can be used for cooling of the space while during the solidification of the PCM a large amount of heat will be realized and can be used for heating the surrounding medium. PCMs have many applications, such as thermal storage of solar energy [1], air-conditioning system [2], thermal protection of electronic devices [3], thermal protection of food [4], spacecraft thermal systems [5], etc.

Although PCMs like paraffin have useful properties as PCM such as low corrosion and chemical stability, but they present low thermal conductivity leading slow in charging and discharging rates and degradation in performance of systems.Heat transfer in the phase change problem was also numerically studied using pure conduction approach. However the problem will be moved to a different level of complexity once convection in the melting zone being accounted for. Research workers used different parameters to assess the heat transfer enhancement in the PCMs.

Jegadheeswaran and Pohekar [6] reviewed the influence of enhancement techniques on the thermal response of the PCM.De Jong and Hoogendoorn [7] utilized two kinds of metal materials to improve the heat transport of latent heat storage systems. The aluminum honeycombs and aluminum thin-strip matrices were both utilized. Based on the experimental results, both structures can apparently reduce the solidification times with a factor up to 7 compared to the original PCM. Bugaje [8] experimentally studied the enhancement of thermal response of a latent heat storage system. A paraffin wax and aluminum matrix were selected as the PCM and the promoter, respectively. The effects of four kinds of matrices and two volume fractions on the thermal response were investigated. Nayak, Saha, Srinivasan [9] developed a numerical model to study the effects of the utilization of PCM with thermal conductivity enhancers on the heat transfer performance of a heat sink used for cooling of electronics. The transient phase change effect

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was simulated by the single-domain enthalpy porosity approach with the solid-liquid interface assumed to be a mushy region. A parametric study was then conducted by varying in turn the Darcy number and the volume fraction.

One of the best techniques to enhance the thermal conductivity of PCMs is adding matrix structure. This is probably due to the simplicity, ease in fabrication and low cost of construction. There are some numerical investigations in heat transfer in fibrous material, but most of them have been restricted to single phase heat transfer problems. In many researches natural convection of the PCM during melting process is ignored. However, in addition to heat conduction, natural convection of the fluid occupying the void spaces of the solid matrix may strongly influence the melting process. Also in some researches it is assumed both the fluid phase and solid matrix are at the same temperature and heat transfer in porous media is modeled using local thermal equilibrium, therefore it is analyzed with one-equation model. But when the temperature difference between solid and fluid phase is important, one equation model need to be replaced with two equation model.

In this work, the low thermal conductivity of PCMs is enhanced by embedding a metal matrix. The momentum conservation of liquid PCM is modeled with Darcy's law with the Brinkman Forchheimer's extension and because of the large difference in thermal properties between solid matrix and PCM, energy transport is studied using two equations model. The equations are numerically solved and the results has been compared with available data good agreement was found with existing both experimental and numerical ones. In addition, the effects of the porosity, thermal conductivity, hot wall temperature and aspect ratio on the melting process has been analyzed.

Mathematical Modeling: Fig. 1 shows the physical domain. It is a cavity filled with high thermal conductivity porous matrix which is saturated with low thermal conductivity PCM.

The right side and top and bottom surfaces are considered adiabatic. The left surface is assumed to be at constant temperature over the melting temperature. The liquid PCM is assumed to be incompressible, have constant properties, Newtonian and the volume change due to the melting process is neglected. The flow and heat transfer are two-dimensional and laminar. The momentum equations include the Brinkman's term and Forcheimer 'extension to Darcy flow, while heat transfer between the porous matrix and PCM in liquid phase is modeled with two temperature model. In order to account for the natural convection effect, the Boussinesq approximation is invoked in the fluid phase and thermal dispersion effects are neglected.

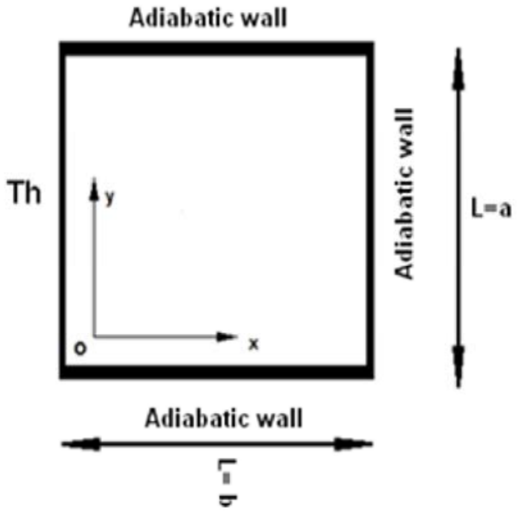

Fig. 1: The thermal cavity

Governing Equations: The mathematical formulation of the governing equations in a can be written as follows:

Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

v-momentum:

$$\frac{\rho_f}{\delta}\frac{\partial v}{\partial t}+\frac{\rho_f}{\delta^2}\frac{\partial(v^2)}{\partial y}+\frac{\rho_f}{\delta^2}\frac{\partial(uv)}{\partial x}= -\frac{\partial \rho}{\partial y}+\frac{\mu}{\delta}\frac{\partial^2 v}{\partial x^2}+\frac{\mu}{\delta}\frac{\partial^2 v}{\partial y^2}-\frac{\mu}{K}v-\frac{\rho_f C_F}{\sqrt{K}}(u^2+v^2)v+\rho_f\beta(T_f-T_{ref}) \tag{2}$$

Liquid PCM energy equation:

$$\varepsilon(\rho c)_f\frac{\partial T_f}{\partial_t}+(\rho c)_f\left(u\frac{\partial T_f}{\partial t}+v\frac{\partial T_f}{\partial y}\right)= \varepsilon k_{feff}\left(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}\right)+h_{\varepsilon f}a_{\varepsilon f}(T_\varepsilon-T_f)-\varepsilon\rho_f L\frac{\partial \delta}{\partial t} \tag{3}$$

Solid matrix energy equation:

$$(1-\varepsilon)(\rho c)_\varepsilon\frac{\partial T_\varepsilon}{\partial t}= (1-\varepsilon)k_{feff}\left(\frac{\partial^2 T_\varepsilon}{\partial x^2}+\frac{\partial^2 T_\varepsilon}{\partial y^2}\right)-h_{\varepsilon f}a_{\varepsilon f}(T_\varepsilon-T_f) \tag{4}$$

Where ε is the solid matrix porosity and δ is the liquid phase fraction.

$$\delta = \text{Liquid fraction of PCM}*\varepsilon \quad (6)$$

$$k_{seff} = (1 - \varepsilon)k_s \quad (7)$$

$$k_{feff} = \varepsilon h_f \quad (8)$$

β is the volumetric expansion coefficient, c_f and c_s are the fluid and solid specific heats at constant pressure, respectively, g is the gravitational acceleration vector, μ is the fluid kinematic viscosity, p is the average pressure read off a pressure gauge, ρ_f and ρ_s are the fluid and solid densities, respectively, t stands for time, T for temperature and u, v represents the Darcy velocities.

In addition, the relationship describing δ as a function of temperature [10]:

$$\delta = (T - (T_m - \Delta T))/(2\,\Delta T) \quad (9)$$

The first term on the right-hand side of the momentum equation represents the pressure drop and the second and third terms on the right-hand side is the Brinkman term, which accounts for the presence of a solid boundary. The forth term, which is known as the Darcian term, accounts for the form drag initiated by the existence of a porous medium. Moreover, the fifth term accounts for the additional pressure drop encountered at high flow rates that is induced by local acceleration and separation around the solid particle. The property values used in the computation are listed in Tables 1 and 2.

The solid matrix of the porous medium constitutes of a fibrous material that may be closely modeled as spherical beads [11]. Accordingly, the geometric function C_F and the permeability of the porous medium K are based on Ergun's model [12] as:

$$K = \frac{\delta^{\varepsilon} d_p}{150(1-\delta)^2} \quad (10)$$

$$CF = \frac{1.75}{\sqrt{150\delta^{\varepsilon}}} \quad (11)$$

where d_p is the bead diameter. When the PCM is in a complete molten state, $\delta = \varepsilon$, where ε is the porosity of the metal matrix. Otherwise, when the PCM is fully or partially solid, PCM is modified according to (10).

The specific surface area of the porous medium, a_{sf}, is based on geometric consideration for a spherical bead and is given by Dullien [13] as:

$$a_{\varepsilon f} = \frac{6(1-\varepsilon)}{d_p} \quad (12)$$

Table 1: Paraffin Properties

Fusion point	18.3
ρ [kg/m3]	780
μ [Pa s]	0.00287
cp [J/kg K]	2310
k [W/m K]	0.1505
α [m2/s]	8.35e-8
β [1/K]	9.1e-4
L [J/kg]	228900
Pr	44.06

Table 2: Porous Matrix Properties

	ρ [kg/m3]	Cp [J/kgK]	k [W/mK]
Al	2702	903	237
Cu	8933	385	401

There are some attempts to get the heat transfer coefficient experimentally, however, most of them are for forced convection, no one is about phase change. Since experimental results are not available in the literature for solid-liquid phase change in fibrous material, the correlation proposed by by Wakao, Kaguei and Funazkri [14] is used.

$$h_{\varepsilon f} = k_f \frac{[2 + 1.1\,\mathrm{Pr}^{\frac{1}{\varepsilon}} \left(\frac{(u^2 + v^2)d_p}{v_f}\right)^{\frac{6}{10}}]}{d_p} \quad (13)$$

The initial and Boundary conditions

Initial condition:

$$T(x\ y, 0) = T_{in} \quad (14)$$

Boundary conditions:

$$\frac{\partial T}{\partial x} = 0 \quad \text{at } x = 0,\ y = 0,\ y = 1 \quad (15)$$

$$T = T_h \quad \text{at } x = 1 \quad (16)$$

Numerical Solution: In this study, the governing equation are solved numerically by finite volume method; and coupled continuity and momentum equations is solved by modified SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithms. Central differencing was used for the diffusion terms while upwind differencing was used for the convective terms. The resulting systems of the momentum and energy equations are solved using the simply implicit procedure (SIP) as outlined by Ferziger and Peric [15]. The numerical code is validated by comparing with numerical result of

Table 3: Comparison of present results (for Pr=1, Da=0.01, Ra=105)

	ε = 0.4	ε = 0.6	ε = 0.9
Present	3.022	3.479	3.917
Nithiarasu [16]	2.983	3.555	3.91

Voller [16]. As shown in the Table 3, our predictions for $\varepsilon = 1$ (without porous media) are in a good agreement with phase change material melting.

RESULTS AND DISCUSSION

In this paper, the reason for using the high thermal conductivity fiber matrix is to enhance the effective thermal conductivity of the PCM energy storage and hence, increase the energy absorption rate. So, numerical study has been performed to investigate the effect of inserting a matrix with different porosities and different thermal conductivities on the liquid fraction.

The difference between mid-height temperature and melting temperature are shown in Fig. 2 for porosity equal to 0.95 and for different times (porous media is Nickel). When the PCM is still in solid state, its viscosity is infi, so that natural convection does not take place, but as the PCM becomes liquid after melting ?nishes, the viscosity falls rapidly, so that natural convection can take place, thus as time increases, the interface front gradually moves upwards, meaning more and more of the PCM is being melted.

Fig. 3 shows Mid-height velocity distribution at different times. When the time equal 200s, only a small part of PCM has been melted and natural convection starts. As time goes on, more and more PCM is being melted. From the numerical investigations, the velocities caused by buoyancy force are quite low.

Effect of Porosity: Fig.4 shows a comparison of liquid fraction of PCMs with time in difference porosities (porous media is aluminium). As the porosity decreases, the melting rate increases and also, the convection motion of the liquid phase damps due to the decrease in the matrix permeability. It is also observed that the rate of increase of thermal conductivity is quite higher than the decrease of natural convection.

Effect of Pore Diameter: Fig. 5 presents the liquid fraction of PCMs at different pore diameter and constant porosity. Metal fiber with smaller pore diameter has better heat transfer performance. This is reasonable because smaller diameter re results has larger contact area between the PCM and porous media for transferring heat.

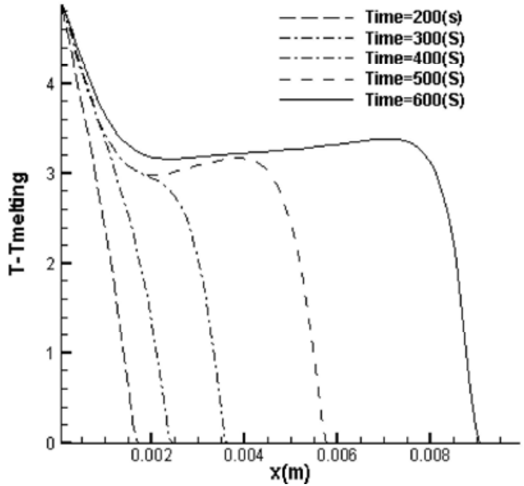

Fig. 2: Mid-height temperature distribution at different times

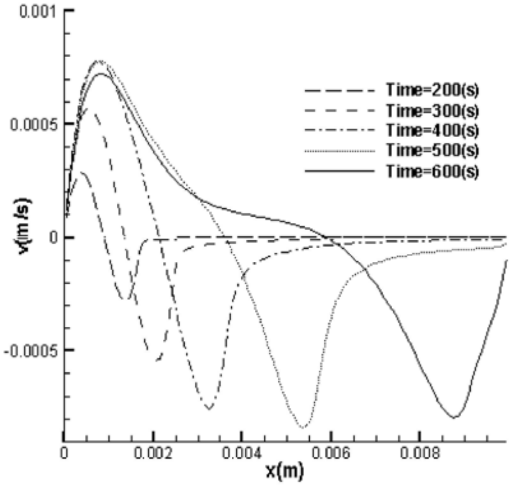

Fig. 3: Mid-height velocity distribution at different times

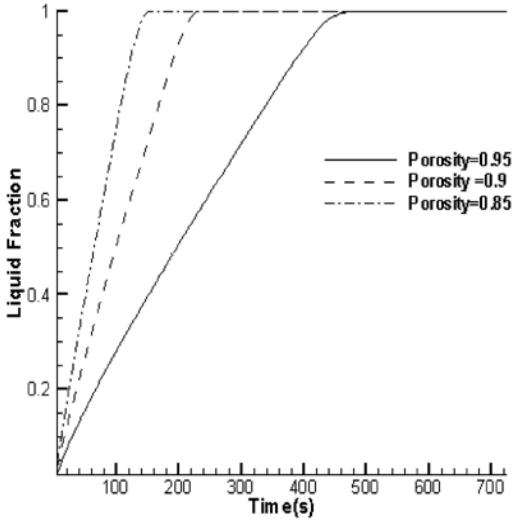

Fig. 4: Effect of porosity on liquid fraction

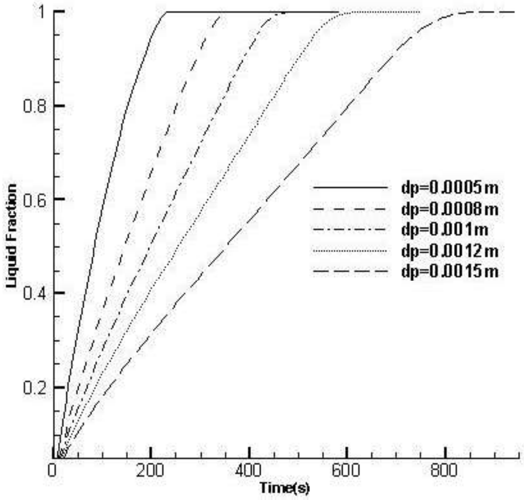

Fig. 5: Effect of pore diameter on liquid fraction

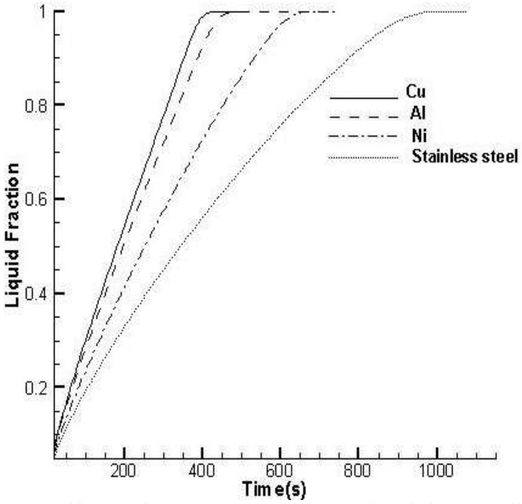

Fig. 6: Effect of porous matrix conductivity on liquid fraction

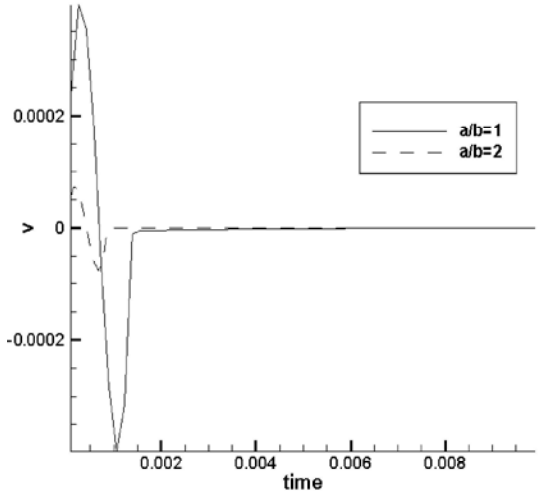

Fig. 7: Mid-height vertical velocity distribution at different aspect ratio

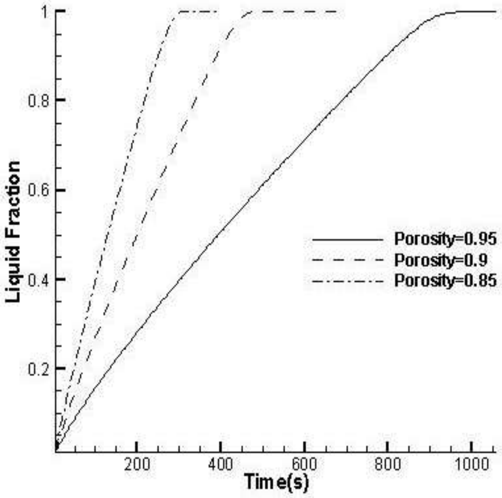

Fig. 8a: Effect of hot wall temperature on liquid fraction(T-T $_{\text{melting}}$= 2.5 °C)

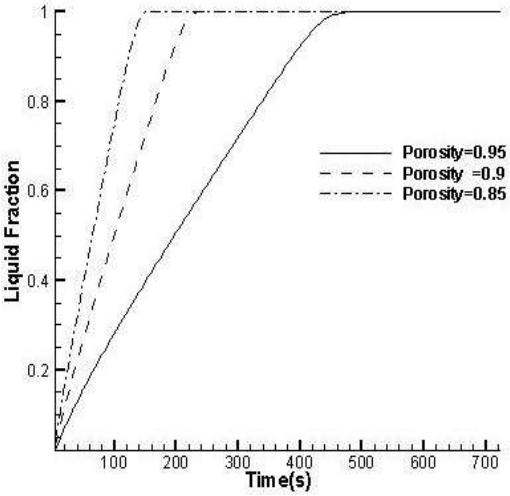

Fig. 8b: Effect of hot wall temperature on liquid fraction (T-T $_{\text{melting}}$= 5 °C)

Effect of Conductivity: To investigate the effect of changing the porous matrix thermal conductivity, two different materials, namely aluminium matrix, nickel, stainless steel and copper matrix are investigated. The porosity is constant at 0.95. It is seen from this Fig.6, the cupper porous matrix (because of higher thermal conductivity) increases heat transfer rate higher than others materials.

Effect of Aspect Ratio: Fig.7 shows a comparison of velocities in central y-direction at constant time and two different aspect ratio. The velocities caused by buoyancy force are quite low and it is observed that increasing in aspect ratio has decreased the melting rate. Decreasing in velocity occurred early.

Effect of Hot Wall Temperature: The intensity of the natural convection in the PCM mainly depends on two factors: its driving force and its resisting force. The driving force increases with increasing temperature differences, whilst the resisting force can be reduced by decreasing the viscosity of the PCM. Fig 8 show liquid fraction of PCM in two difference hot wall temperature. As shown in Fig 8, 9 influence of porous media in difference hot wall temperature similar to each other. When porosity decreases melting rate increases. (Fig 8(a).8(b):T-T $_{\text{melting}}$= 2.5 °C and T-T $_{\text{melting}}$= 5 °C respectively.)

CONCLUSION

A numerical model based on solving the volume averaged conservation equations for mass, momentum and energy with phase change (melting) has been developed to study the effect of adding a high thermal conductivity matrix on the performance of PCM energy storage. A parametric study has been performed to study the effect of using a solid matrix with different porosity and thermal conductivity, pore diameter and aspect ratio. It was found that the presence of the matrix with high thermal conductivity, low porosity and small pore has a great effect on the heat transfer and melting rate of the PCM.

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