



Investigation on the effect of metal foam properties on the PCM melting performance subjected to various heat fluxes

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Abstract

The purpose of this paper is to analyze the effects of structural and mechanical characteristics of metal foam on the melting behavior of phase change materials (PCMs) under the influence of different heat fluxes. To achieve this aim, a two-dimensional numerical model considering the non-equilibrium thermal factor, non-Darcy effect and local natural convection was used. The governing equations of PCM and metal foam are discretized using a finite volume method with a collocated grid arrangement. To simulate the melting of PCM, the enthalpy-porosity method is applied which computes the liquid fraction at each iteration, based on the enthalpy balance. The effect of metal foam characteristics (porosity, pores size and base material) and wall heat flux on the PCM melting time were investigated. The result showed that for both wall heat fluxes (4000 W m^{-2} and 8000 W m^{-2}), foam structure and its mechanical properties have a significant influence on the PCM melting time which these effects should be considered.

Keywords:

Thermal energy storage, PCM, Porous medium properties, Non-equilibrium model, wall heat flux

1. Introduction

Phase change materials are widely used in renewable energy storage systems, especially in the fields of solar energy utilization [1], building energy conservation [2] and battery thermal management [3]. Similar to any other system, PCMs (Phase Change Materials) have some disadvantages. One drawback of most PCMs is their low thermal conductivity that slows down the melting/freezing rate of PCMs. One of the best techniques to compensate their low thermal conductivity is impregnating PCMs into a continuous light-weight porous structure with high thermal conductivity.

Several numerical studies have been performed to investigate the heat transfer characteristics of PCM in metal foam because of its good mechanical and thermo-physical properties. Lafdi et al. [4] numerically investigated the heat transfer and the liquid motion of the molten PCM using a thermal non-equilibrium model. It was indicated that the decrease of the porosity significantly accelerated the melting process due to high thermal conductivity of the graphite foam. Liu et al. [5] numerically

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investigated the melting characteristics of PCM in porous media. Moreover, they studied the effects of the porous media parameters on the thermal performance of a thermal storage unit. Mesalhy et al. [6] established a two-temperature energy equation model to predict the effects of metal foam porosities on the thermal performance of a LTES system. Krishnan et al. [7] numerically analyzed the melting of metal foam/PCM composite in the case of step change of the boundary temperature. The heat transfer between PCM and metal foam was modeled by empirical correlations in their research. Yang and Garimella [8] carried out a numerical simulation utilizing the two-equation non-equilibrium heat transfer model to investigate the melting process of PCM embedded in metal foams, and studied the effect of volume shrinkage/expansion of the PCM on the heat transfer between the PCM and metal foam.

To optimize the heat transfer of PCM/foam composites, it's necessary to realize the effects of foam properties on the melting time of PCMs that has received little attention in previous research. Thus, this study aims to investigate the influence of foam material and its structure (foam porosity and pore sizes) on the melting performance of PCM saturated in porous metal foam. A two-temperature energy model base on enthalpy method has been used to study the phase change process of aluminum foam/PCM composite with different foam porosities ($\epsilon = 0.9, 0.95$) and pores size ($PPI^1 = 10, 40$) under two heat fluxes of 4000 W m^{-2} and 8000 W m^{-2} . Moreover, the results were compared with copper foam/PCM composites with the same structures to investigate the foam mechanical properties influence on the PCM melting time.

2. Problem statement and formulation

The schematic representation of the present study is shown in Fig. 1. The physical domain is a 2D enclosure that the left side was subjected to a heat flux of 4000 W m^{-2} for case 1 and 8000 W m^{-2} for case 2 and other three sides can be considered adiabatic. The enclosure of size $70 \text{ mm} \times 31.5 \text{ mm}$ was considered for both cases and the initial temperature was set at 25°C .

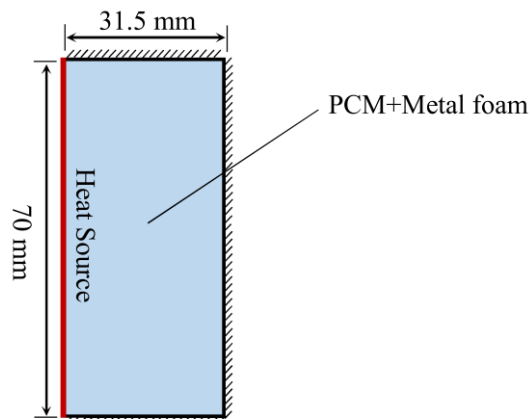


Fig. 1. Schematic diagram of the physical domains

The initial condition and boundary condition are described by the following expressions:

- Initial condition:

¹ Pores per inch

$$0 \leq x \leq 31.5\text{mm}, 0 \leq y \leq 70\text{mm}, u = v = 0, T_{\text{foam}} = T_{\text{pcm}} = T_0$$

- Boundary condition:

$$x = 0, 0 \leq y \leq 70\text{mm}, u = v = 0, q_{\text{foam}} + q_{\text{pcm}} = (1 - \varepsilon)q_w + \varepsilon q_w$$

$$x = 31.5\text{mm}, 0 \leq y \leq 70\text{mm}, u = v = 0, \frac{\partial T}{\partial x} = 0;$$

$$0 \leq x \leq 31.5\text{mm}, y = 0, u = v = 0, \frac{\partial T}{\partial y} = 0;$$

$$0 \leq x \leq 31.5\text{mm}, y = 70\text{mm}, u = v = 0, \frac{\partial T}{\partial y} = 0;$$

The metal foam is assumed homogeneous and isotropic, the Boussinesq approximation is used to account for density variation and the volume variation associated with the phase transition of PCM is neglected. Moreover, a two-temperature energy model was utilized to describe the thermal non-equilibrium between the PCM and aluminum foam. Based on the above-mentioned considerations, the governing equations for PCM and the metal foam can be written as follows:

Continuous equation:

$$\frac{\partial \rho_{\text{pcm}}}{\partial t} + \rho_{\text{pcm}} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0 \quad (1)$$

Momentum equations:

$$\frac{\rho_{\text{pcm}}}{\varepsilon} \frac{\partial u}{\partial t} + \frac{\rho_{\text{pcm}}}{\varepsilon^2} \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \frac{\mu_{\text{pcm}}}{\varepsilon} \nabla^2 u - \left(\frac{\mu_{\text{pcm}}}{K} + \frac{\rho_{\text{pcm}} C}{K^{1/2}} |u| \right) u - \frac{(1 - \beta)^2}{\beta^3 + \delta} A_m u \quad (2)$$

$$\begin{aligned} \frac{\rho_{\text{pcm}}}{\varepsilon} \frac{\partial v}{\partial t} + \frac{\rho_{\text{pcm}}}{\varepsilon^2} \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = & -\frac{\partial p}{\partial y} + \frac{\mu_{\text{pcm}}}{\varepsilon} \nabla^2 v - \left(\frac{\mu_{\text{pcm}}}{K} + \frac{\rho_{\text{pcm}} C}{K^{1/2}} |v| \right) v - \frac{(1 - \beta)^2}{\beta^3 + \delta} A_m v \\ & + \rho_{\text{pcm}} g \gamma (T_{\text{pcm}} - T_{\text{init}}) \end{aligned} \quad (3)$$

Energy equation for PCM:

$$\varepsilon \rho_{\text{pcm}} \left(c_{\text{pcm}} + L \frac{d\beta}{dT_{\text{pcm}}} \right) \frac{\partial T_{\text{pcm}}}{\partial t} + \rho_{\text{pcm}} c_{\text{pcm}} \left(u \frac{\partial T_{\text{pcm}}}{\partial x} + v \frac{\partial T_{\text{pcm}}}{\partial y} \right) = (k_{\text{pcm},e}) \nabla^2 T_{\text{pcm}} + h_{\text{sf}} a_{\text{sf}} (T_s - T_{\text{pcm}}) \quad (4)$$

Energy equation for metal foam:

$$(1 - \varepsilon) \rho_s c_s \frac{\partial T_s}{\partial t} = k_{s,e} \nabla^2 T_s - h_{\text{sf}} a_{\text{sf}} (T_s - T_{\text{pcm}}) \quad (5)$$

Where μ_{pcm} , c_{pcm} , ρ_{pcm} , L and γ are thermal properties of the PCM, presented in Table 1. The density (ρ_s), heat capacity (c_{ps}) and the thermal conductivity (k_s) of aluminum are $2700 \text{ (kg m}^{-3}\text{)}$, $900 \text{ (J kg}^{-1} \text{ K}^{-1}\text{)}$ and $209 \text{ (W m}^{-1} \text{ K}^{-1}\text{)}$, respectively and ε is the porosity of the metal foam. T_{pcm} and T_s were the temperatures of the paraffin and aluminum foam, respectively. A_m is a constant parameter, between 10^5 and 10^8 and δ is a constant to avoid being divided by zero which is 0.0001. β is the liquid fraction during phase change which varies from 0 (solid) to 1 (liquid) and can be defined as:

$$\beta = \begin{cases} 0, & T_{pcm} < T_{m1} \\ (T_{pcm} - T_{m1}) / (T_{m2} - T_{m1}), & T_{m1} \leq T_{pcm} < T_{m2} \\ 1, & T_{pcm} \geq T_{m2} \end{cases} \quad (6)$$

Where, T_{m1} and T_{m2} were the lower and upper limits of the melting temperatures of PCM.

The interfacial surface area (a_{sf}) of the aluminum foam and the interstitial heat transfer coefficient (h_{sf}) can be determined as follows [9]:

$$a_{sf} = \frac{3\pi d_f}{d_p^2} \quad (7)$$

$$h_{sf} = \begin{cases} 0.76 \text{Re}^{0.4} \text{Pr}^{0.37} k_f / d_f, & 0 < \text{Re} \leq 40 \\ 0.52 \text{Re}^{0.5} \text{Pr}^{0.37} k_f / d_f, & 40 < \text{Re} \leq 1000 \\ 0.26 \text{Re}^{0.6} \text{Pr}^{0.37} k_f / d_f, & 1000 < \text{Re} \leq 20000 \end{cases} \quad (8)$$

For the effective thermal conductivity, the model proposed by Boomsma and Poulikakos [10] was adopted as shown by the following equations:

$$k_{eff} = \frac{1}{\sqrt{2}(R_A + R_B + R_C + R_D)} \quad (9)$$

$$R_A = \frac{4\sigma}{(2e^2 + \pi\sigma(1-e))k_s + (4 - 2e^2 - \pi\sigma(1-e))k_{npcm}} \quad (10)$$

$$R_B = \frac{(e - 2\sigma)^2}{(e - 2\sigma)e^2k_s + (2e - 4\sigma - (e - 2\sigma)e^2)k_{npcm}} \quad (11)$$

$$R_C = \frac{(\sqrt{2} - 2e)^2}{(2\pi\sigma^2(1 - 2\sqrt{2}e))ks + 2(\sqrt{2} - 2e - \pi\sigma^2(1 - 2\sqrt{2}e))k_{npcm}} \quad (12)$$

$$R_D = \frac{2e}{e^2ks + (4 - e^2)k_{npcm}} \quad (13)$$

Where

$$\sigma = \sqrt{\frac{\sqrt{2(2 - (5/8)e^3\sqrt{2} - 2\varepsilon)}}{\pi(3 - 4\sqrt{2}e - e)}}, \quad e = 0.339 \quad (14)$$

The effective thermal conductivities of PCM and metal foam can be defined as below:

$$\begin{aligned} k_{pcm,e} &= k_{eff} | k_s = 0 \\ k_{s,e} &= k_{eff} | k_{pcm} = 0 \end{aligned} \quad (15)$$

Table 1. Thermo-physical properties of paraffin

Parameters	Value
Density of paraffin (kg/m ³)	785.02
Latent heat of paraffin (kJ/kg)	1.021×10^5
Melting temperature of paraffin (°C)	46.48- 60.39
Thermal conductivity of paraffin (solid/liquid) (W/m K)	0.3- 0.1
Specific heat capacity of paraffin (J/kg K)	2850
Dynamic viscosity of liquid paraffin (kg/m s)	3.65×10^{-3}
Thermal expansion coefficient of paraffin (K ⁻¹)	3.085×10^{-4}

For metal foam, the porosity (ε), pore density (ω) and pore size (d_l) are three basic parameters used to describe the structural characteristics of the foam. The ligament diameter could be determined based on pore size (d_p) by the following equations [11-12]:

$$d_f = 1.18 \sqrt{\frac{1-\varepsilon}{3\pi}} d_p \quad (16)$$

Where

$$d_p = \frac{22.4 \times 10^{-3}}{\omega} \quad (17)$$

The permeability (K) and inertial coefficient (C) are determined as [11-12]:

$$K = \frac{\varepsilon^2 d_k^2}{36\chi(\chi-1)} \quad (18)$$

$$C = \frac{0.00212(1-\varepsilon)^{-1.32} (d_f / d_p)^{-1.63}}{\sqrt{K}} \quad (19)$$

Where

$$\chi = 2 + 2 \cos \left(\frac{4\pi}{3} + \frac{1}{3} \cos^{-1} (2\varepsilon - 1) \right) \quad (20)$$

$$d_k = \frac{\chi}{3-\chi} d_p \quad (21)$$

3. Numerical procedure and validation

A code written in Fortran 90 has been developed to analyze the melting problem of phase change materials embedded with metal foam. Finite volume method on collocated grids using the SIMPLEC algorithm was utilized for discretizing all the governing equations and the Rhie and Chow [13] interpolation is also used in order to avoid checker-boarding effect. Moreover, the enthalpy-porosity method [14] is applied to simulate the phase change of PCM.

For the mesh dependency test, three non-uniform grid meshes with the grid sizes 91×71 , 141×101 and 181×121 , are conducted and the result is presented in Fig. 2 where the y-axis represents the PCM solid fraction through the melting process which varies from 1 (for solid PCM) to 0 (for liquid PCM). It is found that the grid 141×101 is sufficiently fine to ensure a grid independent solution for this study. Furthermore, the effects of the time step on the numerical code were checked

using three time steps: 0.2 s, 0.5 s and 1 s that the time step of 0.5 s was found accurate enough to balance the accuracy and the computational time. The computational time for this case was three days using 8 CPU (Intel core i7- 7th generation) processors. Moreover, the convergence criteria for the residuals of continuity equation, velocity and energy equation were set as 10^{-4} , 10^{-4} and 10^{-6} , respectively.

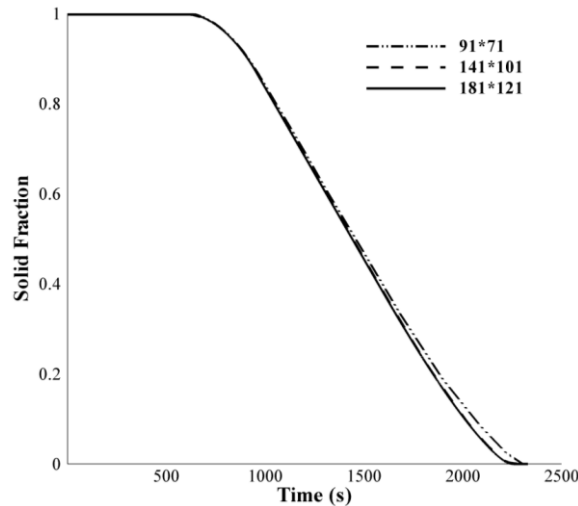


Fig. 2. Mesh dependence analysis

The model used in this study is validated against the experimental results of Lafdi et al. [4]. Fig. 3 shows the comparison of temperature-time history for the heater between the numerical and experimental results. It is obvious that the results predicted by the model show a good agreement with the experimental data.

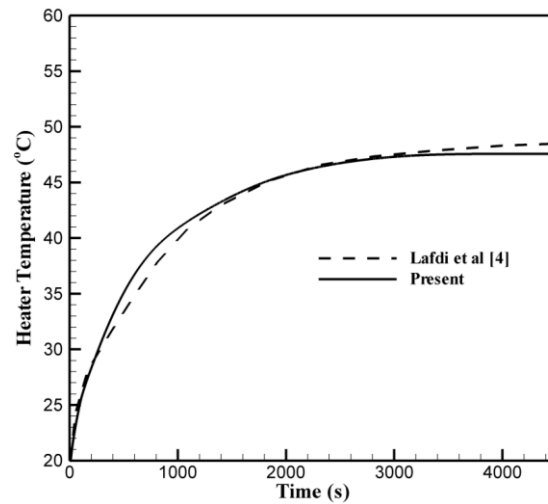


Fig. 3. Comparison of heater temperature variations vs. results by Lafdi et al. [4] (for $\varepsilon=96.6\%$ and $\omega=10$ PPI)

Besides, the numerical code was validated with the Li et al. [15] experimental results by comparing the interface positions at two different moments. Fig. 4(a) and (b) are comparisons of the numerical results with pictures of experimental interface locations at 3600 s and 3780 s for the

0.90 porosity and 10 PPI copper foam. The red color parts belong to melted paraffin and other parts present the solid/liquid interface. The predicted solid/liquid interfaces obtained from the numerical predictions agree well with the experimental results. Thus, the feasibility of the present model is verified.

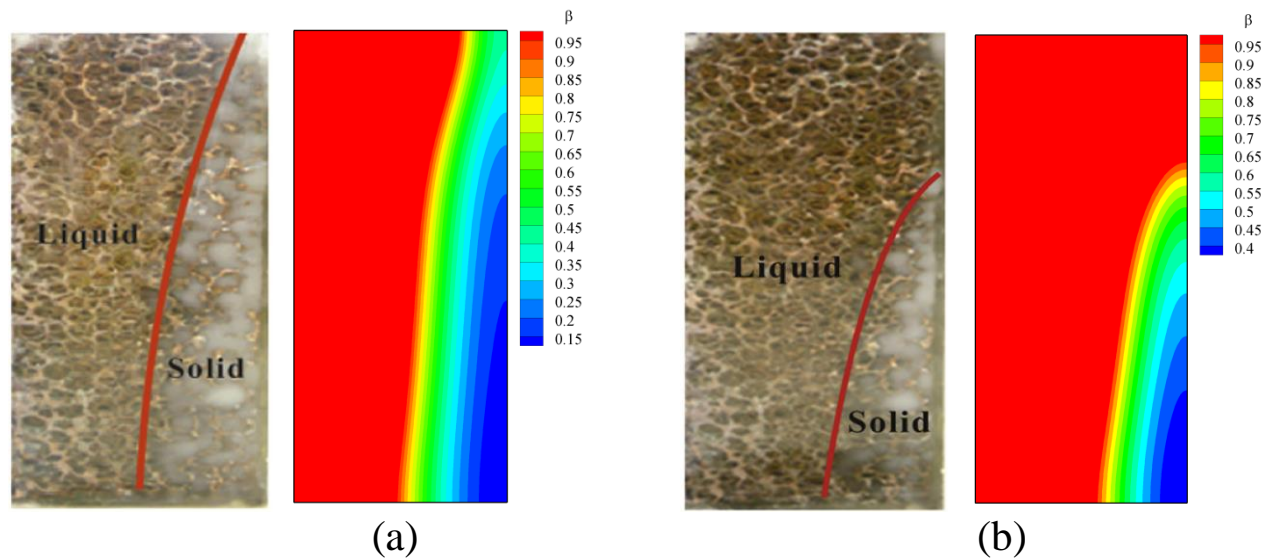


Fig. 4. Comparison of the Melting progress vs. Li et al. [15] experiments for $\varepsilon=90\%$ and $\omega=10$ PPI at (a) $t=3600s$ and (b) $t=3780s$

4. Results and discussion

The evolution of the phase-change interface during the melting process under different aluminum-foam configurations and fixed heat flux $Q'' = 4000 \text{ W m}^{-2}$ was illustrated in Figs. 5(a) and (b). It can be seen from the results that almost for all the cases before $t=1200s$, the solid-liquid interfaces are parallel to the heating surface which indicate that conduction is the dominant mechanism in the phase change process and natural convection can be neglected. Moreover, for higher porosities, the solid-liquid interface is thinner than that for lower porosities which can be due to the higher thermal conductivity of lower porosity foams which leads to more uniform temperature distribution. Furthermore, for both porosities at $t=1200s$, the liquid fraction for foams with higher PPI is more than that for lower ones which shows the positive effect of using foams with smaller pores size. The natural convection effect becomes more significant over time as can be seen for $t=2100s$ that enhances the melting rate significantly. Among all cases, it's the foam with $\varepsilon=0.90$ and $PPI=40$ that has melted the whole PCM before 2100s which shows the best melting performance for $Q'' = 4000 \text{ W m}^{-2}$.

Fig. 6(a) and (b) depicted the evolution of the solid-liquid interface with heat flux $Q'' = 8000 \text{ W m}^{-2}$ over time. As the results showed, like the case $Q'' = 4000 \text{ W m}^{-2}$, at the beginning steps of phase change ($t=400s$), higher porous foam has better melting rate compared with lower porous foam and natural convection is more sensible for $\varepsilon=0.95$. While at $t=1000s$, natural convection effect is obvious for both foams and like the previous case, metal foam/PCM composite with lower porosity

and higher PPI has a higher liquid fraction which can be attributed to the higher conduction heat transfer of lower porosity foam.

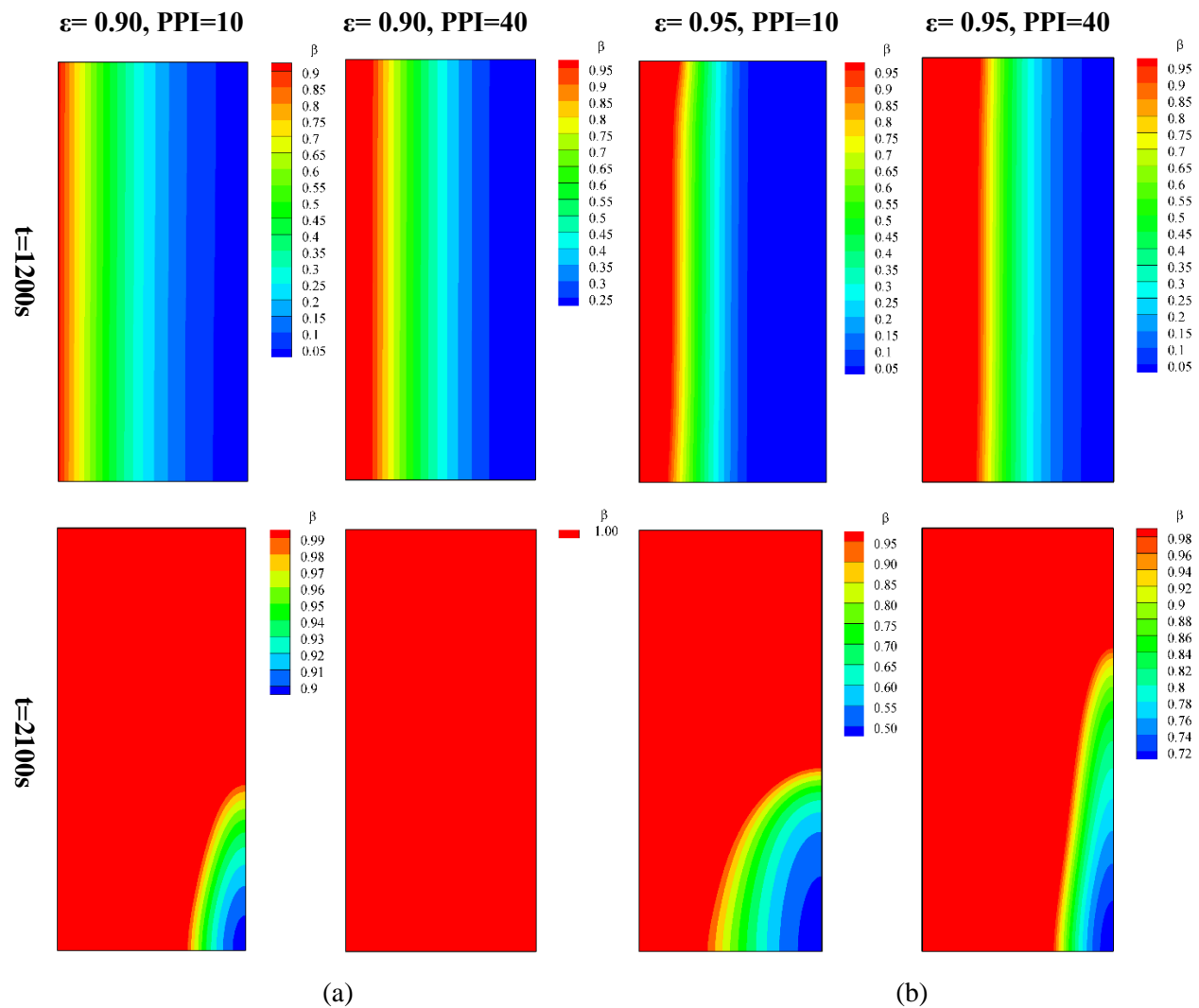


Fig. 5. Melting progress for $Q'' = 4000 \text{ W m}^{-2}$ at $t=1200\text{s}$, 2100s for a) $\varepsilon=0.90\%$ and b) $\varepsilon=0.95\%$

To have a better understanding of the influence of heat flux and foam structure on the melting process, we studied the melting time of various aluminum foam/PCM composites depicted in Figs. 7 and 8. In Fig. 7, it's supposed to have foams with the same porosity and different pores size and in Fig. 8, conversely, the PPI is equal and porosities are different. It can be concluded from Figs. 7 and 8 that for a fixed porosity, foams with higher PPI (lower pores size) have a better melting performance for both cases, $Q'' = 4000 \text{ W m}^{-2}$ and 8000 W m^{-2} . However, for a fixed PPI, foams with lower porosity have shorter melting time.

Finally, the effect of foam base material has been studied by comparing the melting time results of aluminum foam/PCM composite with the results of copper foam/PCM composite. The density, heat capacity and the thermal conductivity of copper are $8920 \text{ (kg m}^{-3}\text{)}$, $380 \text{ (J kg}^{-1}\text{K}^{-1}\text{)}$ and $401 \text{ (W$

$\text{m}^{-1}\text{K}^{-1}$), respectively. The melting time for various heat fluxes and different foams are presented in Table. 2.

The results showed that for both cases $Q'' = 4000 \text{ W m}^{-2}$ and 8000 W m^{-2} , among foams with porosity of 90%, aluminum foam with PPI=40 and from foams with porosity of 95%, copper foam with PPI=40 have the shortest melting time. It can be attributed to the fact that for higher porosity which the composite has lower amount of metal foam, the importance of foam thermal conductivity is more significant and as copper has higher thermal conductivity than aluminum, the copper foam/PCM composite has shorter melting time. However, among all of the foams studied in this research for both heat fluxes, it was the aluminum foam with $\varepsilon = 0.90$ and PPI=40 which had the best melting performance. Moreover, as expected, increasing heat flux from 4000 W m^{-2} to 8000 W m^{-2} will decrease the melting time for all case which is more sensible for foams with lower porosities. The highest melting decrease was for copper foam with $\varepsilon = 0.90$ and PPI=40 with 46.92% decrement, and the lowest one was for aluminum foam with $\varepsilon = 0.90$ and PPI=40 with 36.11%.

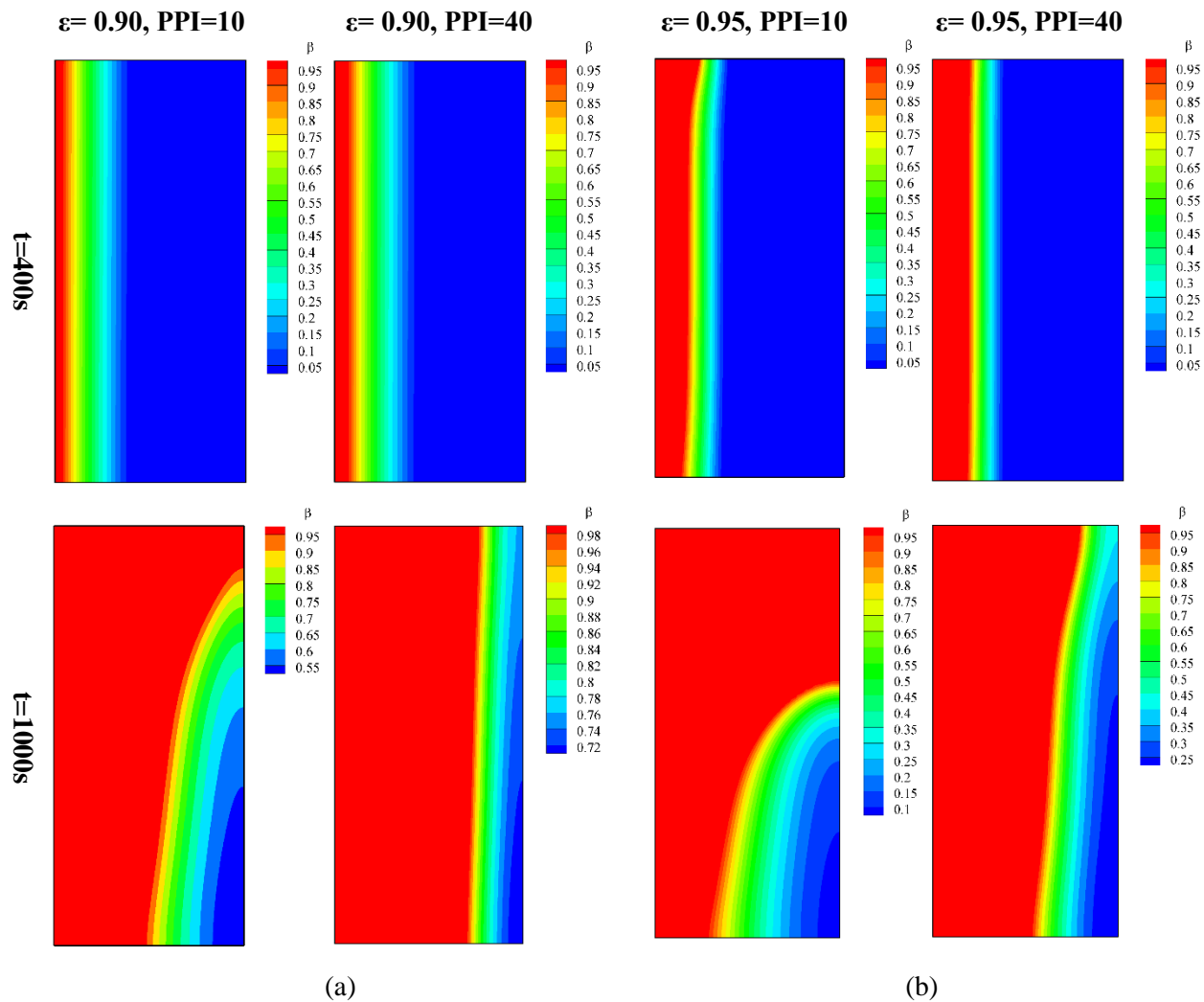


Fig. 6. Melting progress for $Q'' = 8000 \text{ W m}^{-2}$ at $t = 1200\text{s}$, 2100s for a) $\varepsilon = 0.90\%$ and b) $\varepsilon = 0.95\%$

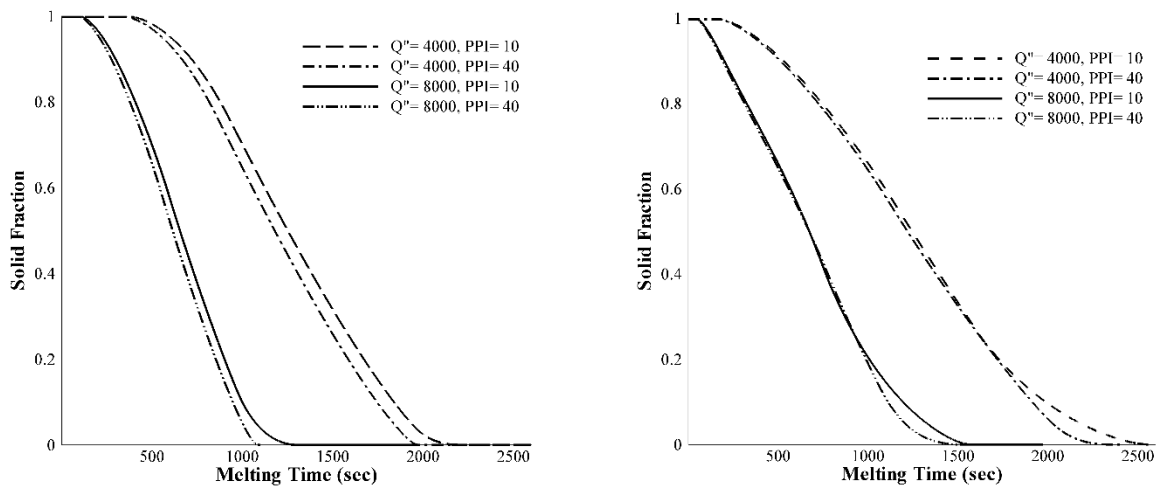


Fig. 7. Comparison of solid fraction vs. melting time for $Q'' = 4000 \text{ W m}^{-2}$ and 8000 W m^{-2} in foams with $\varepsilon = 0.90$ (left) and $\varepsilon = 0.95$ (right)

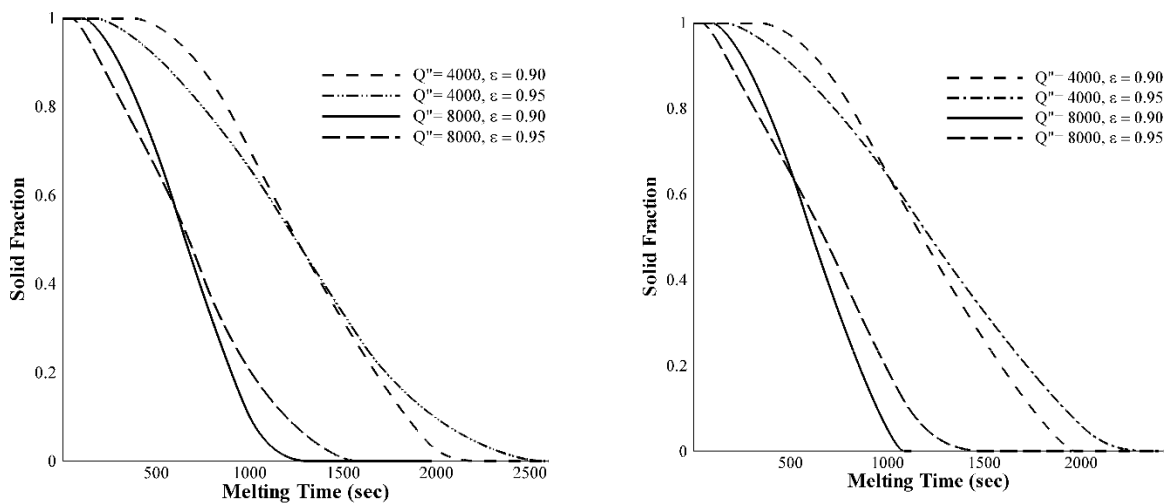


Fig. 8. Comparison of solid fraction vs. melting time for $Q'' = 4000 \text{ W m}^{-2}$ and 8000 W m^{-2} in foams with $PPI = 10$ (left) and $PPI = 40$ (right)

Table. 2. Melting time (s) for various heat fluxes and different foams

Heat flux (W m^{-2})	Material	$\varepsilon = 0.90, PPI = 10$	$\varepsilon = 0.90, PPI = 40$	$\varepsilon = 0.95, PPI = 10$	$\varepsilon = 0.95, PPI = 40$
4000	Al	2200.5	1975.0	2555.0	2334.5
	Cu	2262.5	2078.0	2346.5	2072.0
8000	Al	1295.0	1095.0	1568.0	1491.5
	Cu	1230.0	1103.0	1390.0	1179.0

5. Conclusion

In this study, the effects of heat flux and foam properties on melting process are investigated. The physical model based on finite volume element and non-equilibrium thermal equation is established and validated with experimental data. It turns out that the heater power and foam structure could affect the thermal performance of the foam/paraffin composite significantly. The results revealed that for both copper and aluminum foams, the melting time of paraffin embedded in foam could be improved with decreasing porosity due to the higher conduction heat transfer. However, for lower porosities, aluminum foams and for higher ones, copper foams present better melting performance. Furthermore, for a fixed foam porosity, increasing the PPI will decrease the melting time for both foams because of the larger interfacial area density. Finally, comparing the results for $Q'' = 4000 \text{ W m}^{-2}$ and 8000 W m^{-2} showed that increasing wall heat flux will decrease the melting time up to 46.92% in the best situation. Among all the cases studied in this research, aluminum/PCM composite with $\varepsilon = 0.90$ and $\text{PPI} = 40$ had the best melting time for both wall heat fluxes.

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