Melting and solidification behavior of PCM embedded in metal foam

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Abstract: In this paper, a numerical study is conducted on the melting and solidification process of metal foam/paraffin wax with cyclic heating and cooling. A mathematical model based on the Brinkman-Frochheimer extended Darcy equation and the local thermal non-equilibrium model (LTNE) is proposed. The paraffin phase change is modeled by enthalpy-porosity method. The numerical model is solved using a finite element analysis by the Porous Media and Subsurface flow module (Brinkman Equation (br)), and the local Thermal Non-Equilibrium module in COMSOL Multiphysics 5.3a software. The steps of the numerical model can be summarized as, discretization of the domain and coupled governing equations (element, type, and size), defining the time step and relative and absolute tolerances or errors for the convergence conditions of the solution, determining the nonlinear settings for iteration sequences and selecting the appropriate solver techniques. The numerical results are validated by comparing with experimental data. The phase and temperature fields of PCM embedded in metal foam showed that the conduction is the dominant heat transfer mode during the melting process. It is found that the time of melting was reduced with sinusoidal heating.

Keywords: Thermal energy storage, Numerical simulation, PCM, COMSOL.

Introduction

Phase Change Materials (PCMs) offer the possibility to store and release a large amount of heat at the time of phase change in small volumes. These materials are known for their low thermal conductivity, which reduces the thermal energy storage/release kinetics [1]. The PCMs thermal conductivity can be improved through the addition of materials with high thermal conductivity such as metal fins, expanded graphite [2], and metal foams. Metal foams have specific characteristics such as high porosity (porosity between 0.8 and 0.98), high thermal conductivity [12]. This qualifies them to be a good solution to intensify heat transfer during melting and solidification of PCM [3]. Paraffin (C_nH_{2n+2}) is an excellent PCM for latent heat storage because of its high latent heat and good stability.
One of the challenges is to find the optimal heating and cooling conditions, thermophysical and structural properties of metallic foams that allow the efficient use of these composites to store thermal energy. Numerous numerical and experimental research papers in the literature have been carried out to study the effect of thermal conductivity and microstructure of metal foams on the effective thermal conductivity of MCP/metal foam composites [4]. Sriharsha S. et al [5] studied the effect of pore size on the effective thermal conductivity of a Paraffin-Aluminum Foam composite. It was found that pore size has a significant effect on the effective conductivity. As the pore size decreases, the effective thermal conductivity increases. El Idi et al [6] have shown that the morphology of the metal foam has a great influence on the phase change kinetics of a PCM incorporated in a metal foam. The study of heating and cooling conditions on the kinetics of phase change of PCM embedded in metal foam is necessary for efficient use of PCM- Metal foam composite storage unit [13].
In this paper, we present a numerical study on the solid-liquid phase change of paraffin RT27 embedded in aluminum foam using COMSOL Multiphysics. The Brinkmann-Forchheimer extended Darcy equation and the local thermal non-equilibrium model by applying a two-energy equation is used. The phase change is modeled by enthalpy-porosity method. The numerical results are validated by comparing with experimental data. The effect of boundary condition on the melting and solidification rate of PCM embedded in metal foam is studied. The results will be presented and discussed.

Experimental device

The experimental apparatus consists of a PCM/Metal foam composite container, a heating resistor, a temperature data logger, a PID temperature controller, a computer and CCD camera. The PCM/Metal foam container is a rectangular enclosure with inside dimensions 150mm in width, 170 mm in height and 10mm in depth. **Figure 1** present a photo of experimental device and **Figure 2** a schematic diagram of the experimental device**.** The right wall of the enclosure served as a constant heat source by heating resistor. In order to visualize the melt front evolution, photographs were taken at time intervals of 3minutes.

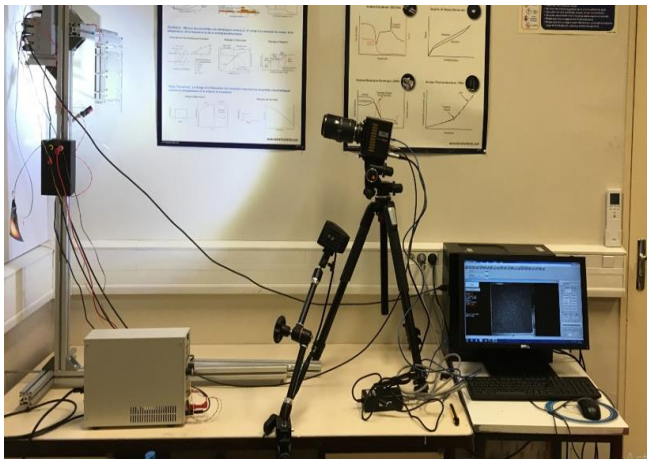


Figure 1. Photo of experimental device

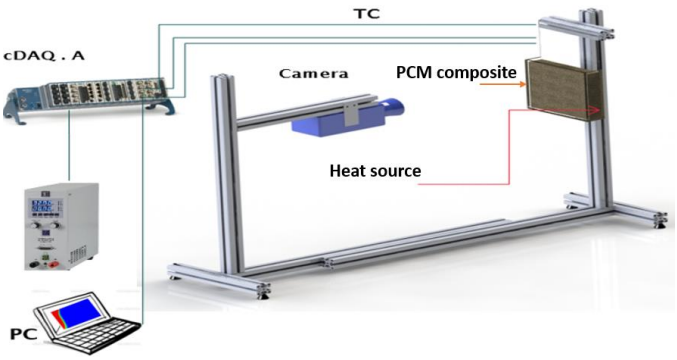


Figure 2. Schematic diagram of the experimental device

Physical model

The physical problem to be tackled is illustrated in **Figure 3**. A square cavity filled with paraffin wax RT27 embedded in a metal foam. The left wall cavity is set to a fixed temperature or a constant/ sinusoidal heat flux. The rest of the wall cavity is insulted. Initially, the metal foam and PCMs in the cavity are uniformly under the melting temperature. The proprieties of paraffin RT27 used for the present study are given in **Table1,** [8].

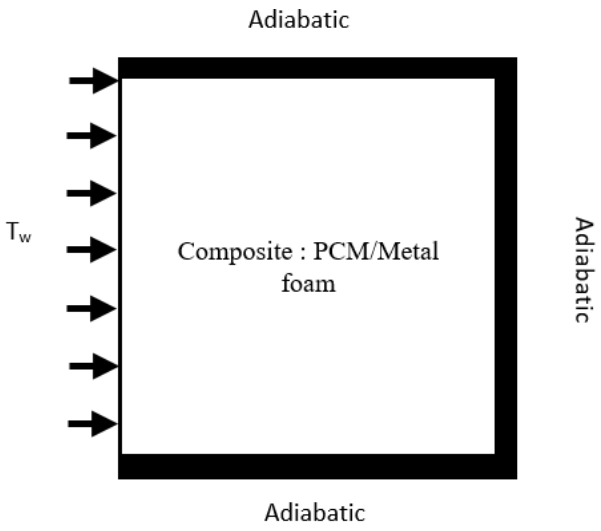


Figure 3. Physical model

Assumptions

The liquid is considered as incompressible and the flow is laminar. The natural convection caused by buoyancy is subject to the Boussinesq approximation. The thermal radiation is neglected in the metal foam during melting. The metal foam is considered as isotropic and homogeneous.

Mathematical model

Based on the above assumptions, the mathematical model for the present problem can be expressed by the following equations [7]:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

Momentum equations:

$$\frac{\rho_p}{\varepsilon}\frac{\partial u}{\partial t}+\frac{\rho_p}{\varepsilon^2}(\vec{V}\vec{\nabla}).u=-\frac{\partial p}{\partial x}+\frac{\mu}{\varepsilon}\nabla^2 u-(\frac{\mu}{K}+\frac{\rho_p C}{\sqrt{k}}|u|)u+S_u \quad (2)$$

$$\frac{\rho_p}{\varepsilon}\frac{\partial v}{\partial t}+\frac{\rho_p}{\varepsilon^2}(\vec{V}\vec{\nabla}).v=-\frac{\partial p}{\partial y}+\frac{\mu}{\varepsilon}\nabla^2 v-(\frac{\mu}{K}+\frac{\rho_p C}{\sqrt{K}}|v|)v+S_v+\rho_p g\beta(T-T_{ref}) \quad (3)$$

Where C: Inertial coefficient ($W.m^{-2}.K^{-1}$), K: Permeability (m^2), $S_u=A\frac{(1-b)^2}{B^3+b}u$, and $S_v=A\frac{(1-b)^2}{B^3+b}v$ denoted the source term to damping the velocity in solidified phase (*A* and *B* are two constants). They are deducted from Carmen-Kozney relation. In this study we take $A=10^5$ and $B=10^{-3}$. For the solidified phase, $b=0$ leads the item to be infinity to damp the velocity in the momentum equation. For fluid phase, $b=1$ leads the item to be zero.

b(T) can be defined as:

$$b(T)=\begin{cases}0 & T<(T_m-\Delta T/2)\\ \dfrac{T-T_m+\Delta T/2}{\Delta T} & (T_m-\dfrac{\Delta T}{2})\le T<(T_m+\dfrac{\Delta T}{2})\\ 1 & T>(T_m+\Delta T/2)\end{cases}$$

Equations of continuity and momentum, it's also available for PCM filled in the cavity by taken porosity equal 1.

There existed a large difference in thermophysical properties between the metal foam and PCM saturating [6,12]. We have two energy equations:

Energy equation for PCM:

$$\varepsilon\rho_p C_p\frac{\partial T_f}{\partial \tau}+\rho_p C_p(u\frac{\partial T_p}{\partial x}+v\frac{\partial T_p}{\partial x})=k_p\nabla^2 T_p+h_{ps}a_{ps}(T_s-T_p) \quad (4)$$

The density variation of PCM can be given by:

$$\rho_p(T)=\rho_{ps}+(\rho_{pl}-\rho_{ps}).b(T) \quad (5)$$

The phase change temperature interval is taken at 3°C [8]. The specific heat of PCM can be written as:

$$C_{pp}=C_{ps}+(C_{pl}-C_{ps}).b(T)+L_f D(T) \quad (6)$$

Where L_f is the latent heat of fusion and:

$$D(T)=e^{\left(\frac{-(T-T_m)^2}{(\Delta T/4)^2}\Big/\sqrt{\pi(\Delta T/4)^2}\right)} \quad (7)$$

D is a smoothed Delta Dirac function which is zero everywhere except in the interval. Its integral equal to 1. The use of this function ensures that the latent heat is conserved during melting process. The thermal conductivity of PCM can be given as:

$$k_{Pe}(T) = k_{Ps} + (k_{Pl} - k_{Ps}).b(T) \quad (8)$$

Energy equation for metal foam:

$$(1-\varepsilon)\rho_S c_{PS} \frac{\partial T_S}{\partial \tau} = k_{Se}\nabla^2 T_S - h_{PS} a_{PS}(T_S - T_P) \quad (9)$$

Where k_{Pe}, k_{Se} and h_{PS} were –respectively- effective thermal conductivity of paraffin, effective thermal conductivity of metal foam and the interstitial heat transfer coefficient between the porous metallic surface and saturating PCM. Zukauskas [10] semi-empirical model was used to estimate.

$$h_{PS} = \begin{cases} 0.76\,\mathrm{Re}^{0.4}\,\mathrm{Pr}^{0.37}\,\dfrac{k_P}{d} & 0 < \mathrm{Re} \le 40 \\ 0.52\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.37}\,\dfrac{k_P}{d} & 40 < \mathrm{Re} \le 1000 \\ 0.26\,\mathrm{Re}^{0.6}\,\mathrm{Pr}^{0.37}\,\dfrac{k_P}{d} & 1000 < \mathrm{Re} \le 20000 \end{cases} \quad (10)$$

Many models having been developed to describe the effective thermal conductivity. The tetrakaidecahedron cell model proposed by Boomsma et al [9] was adopted to describe the thermal conductivity in the present study.

$$k_{Pe} = k_{eff}\big|k_s = 0 \quad (11)$$

$$k_{Se} = k_{eff}\big|k_f = 0 \quad (12)$$

Where

$$k_{eff} = \frac{\sqrt{2}}{2\left(R_A + R_B + R_C + R_D\right)} \quad (13)$$

$$R_A = \frac{4d}{\left(2e^2 + \pi d(1-e)\right)k_s + \left(4 - 2e^2 - \pi d(1-e)\right)k_f} \quad (14)$$

$$R_B = \frac{(e-2d)^2}{(e-2d)e^2 k_s + \left(2e - 4d - (e-2d)e^2\right)k_f} \quad (15)$$

$$R_C = \frac{(\sqrt{2}-2e)^2}{2\pi d^2\left(1-2e\sqrt{2}\right)k_s + 2\left(\sqrt{2}-2e-\pi d^2(1-e\sqrt{2})\right)k_f} \quad (16)$$

$$R_D = \frac{2e}{e^2 k_s + \left(4-e^2\right)k_f} \quad (17)$$

$$d = \sqrt{\frac{\sqrt{2}(2-(5/8)e^3\sqrt{2}-2\varepsilon)}{\pi\left(3-4e\sqrt{2}-e\right)}}, \quad \text{e=0.339} \quad (18)$$

Thermophysical and structural proprieties of metal foam

Thermophysical proprieties of aluminum foam used in this study are presented in **Table 1**. Several studies have been carried out to develop an analytical model for predicting permeability and the inertial coefficient of metal foam. In this work, we use the model of Calmidi [11] to calculate permeability and the inertial coefficient.

Permeability:

$$K = 0.00073 d_p^2 (1-\varepsilon)^{-0.224}\left(\frac{d_f}{d_p}\right)^{-1.11} \quad (19)$$

Inertial coefficient:

$$C = 0.00212 d_p^2 (1-\varepsilon)^{-0.132}\left(\frac{d_f}{d_p}\right)^{-1.63} \quad (20)$$

Where d_f denotes the equivalent diameter of metal foam fibers and pore diameter:

$$\frac{d_f}{d_p} = 1.18\sqrt{\frac{1-\varepsilon}{\pi}}\left(\frac{1}{1-e^{-(1-\varepsilon)/0.04}}\right) \quad (21)$$

d_p can be calculated from pore density:

$$d_p = \frac{0.0254}{PPI} \quad (22)$$

The specific area can be calculated by the following formula:

$$a_{PS} = \frac{3\pi d_f (1-e^{-((1-\varepsilon)/0.004)})}{(0.59 d_p)^2} \quad (23)$$

Table 1: Thermphysical properties

Paraffin RT27	
Density *(kg.m^{-3})*	870
Heat capacity–solid *(J.K^{-1}.kg^{-1})*	2400
Latent heat *(kJ.kg^{-1})*	179
Melting temperature *(K)*	300.15
Dynamic viscosity *(Kg.m^{-1}.s^{-1})*	3.42x10^{-3}
Thermal conductivity –solid *(W.K^{-1}.m^{-1})*	0.24
Density – liquid *(kg.m^{-3})*	760
Heat capacity –liquid *(J.K^{-1}.kg^{-1})*	1800

Thermal conductivity – liquid *(W.K^{-1}.m^{-1})*	0.15
Thermal expansion, β (K^{-1})	0.5x10^{-3}
Aluminum Foam	
Density *(kg.m^{-3})*	2800
Heat capacity *(J.K^{-1}.kg^{-1})*	910
Thermal conductivity *(W.K^{-1}.m^{-1})*	237

Solution with COMSOL Multiphysics

We use three different physics interfaces of COMSOL Multiphysics® to model the phase change of PCM in metal foam. The fluid flow is modeled using Brinkman equation *(br)* model for the non-Darcian porous media. Heat transfer in solid *(ht1)* and heat transfer in fluid *(ht2)* was used respectively to model heat transfer in metal foam and PCM. To couple the heat transfer in solid (metal foam) and fluid (PCM) we select the local non- thermal equilibrium interface. Brinkman equation (br) and heat transfer in fluid is coupled used the flow coupled interface *(fc)*.

Model validation

The numerical model is solved using a finite element analysis with COMSOL Multiphysics 5.3a software. **Figure 4** present a comparison of the evolution of the experimental and numerical liquid fraction for a Nickel foam/ RT27 composite, for a duration of about 10 hours. It is a nickel foam with a size 150*150*10mm, a porosity of 0.95 and a pore diameter of 2.3mm filled with RT27 paraffin. The composite is initially in thermal equilibrium at a temperature of 21°C, which is the ambient temperature. At time t>0, a temperature Tw=31°C is imposed on the west wall. The liquid fraction of the paraffin was calculated using a Matlab program. The method of calculating the experimental liquid fraction consists in converting the photos taken by the CCD camera to binary images. Then the liquid fraction is deduced from the calculation of white and black pixels. We can see that there is a good agreement between the experimental and numerical results, which allows us to validate our numerical model.

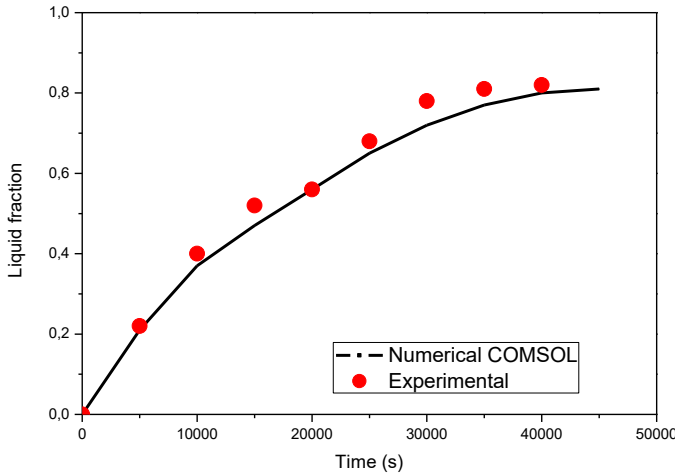
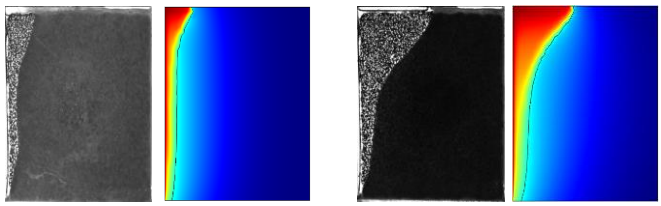


Figure 4. Comparison between numerical results and experimental data

The comparison of the solid-liquid interface locations between the experimental and numerical results is shown in **Figure 5**. The predicted locations of solid-liquid phases by our numerical model agree well with the locations in experimental results. As a conclusion, the COMSOL numerical model could be applied to investigate the heat transfer and solid-liquid phase change process of the paraffin RT27 embedded in metal foam.



(a) (b)

Figure 5. Metling front, numerical Vs experimental. (a) after 3600s and (b) after 10800s.

Results

In this section, we present the results of paraffin wax RT27 melting process in the same conditions as RT27/Aluminum foam composite with T_w=303.15 K. **Figure 6** present temperature and phase fields during the melting process. The red part represents liquid phase and the blue part represents the solid phase and other colors represent the mushy zone. The black vectors represent the velocity field. After 10 minutes, the interface is almost parallel with the hot wall indicate that the heat conduction is the dominated heat transfer mechanism. After 30 minutes we show the modification of the interface shape. The liquid near the hot wall (heat source) is heated and rises up due to the buoyancy forces. The solid PCM on the top will be melted by the hot liquid. And then the PCM liquid down to the bottom, and temperature decreases gradually. Therefore, the natural convection will be generated, due to the hot liquid circulation, the PCM solidly in the top will be melted faster than in the bottom. The velocity vectors show clearly the circulation of liquid PCM. The curve shape of the solid - liquid interface, it's due to the natural convection phenomena.

Figure 7 present temperature and phase fields of RT27/ Aluminum foam with a porosity of 0.93 and pores density 40PPI, during melting with Tw=32°C. The phase and temperature fields show that the heat conduction, it's the

dominant heat transfer mechanism during melting. Larger pore density (40PPI) reduces permeability, and suppress natural convection [6].

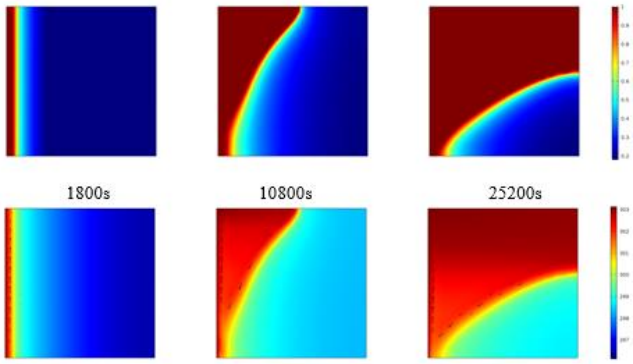


Figure 6. Phase change and temperature field RT27

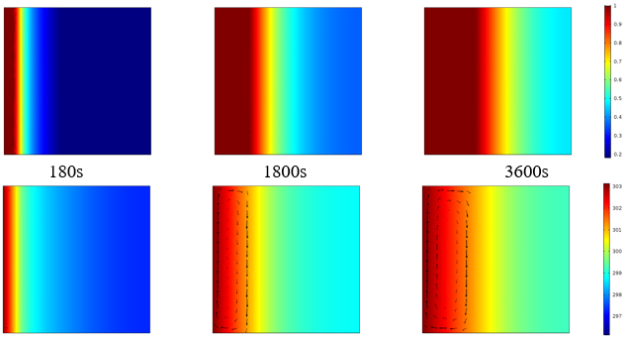


Figure 7. Phase change and temperature field RT27- Metal foam composite

Effect of boundary condition on the melting and solidification

In order to study the effect of boundary condition on the melting and solidification of PCM incorporated in a metal foam a cyclic heating and cooling study was carried out. The PCM composite are widely used in buildings, which affected by the variation in energy solar radiation and to cool electronic devices that generate a constant heat flux. In this section we present a study in the cyclic heating and cooling effects on the phase-change kinetic of paraffin RT27 embedded in aluminum foam used as an energy storage system. There are a two types of cycling heating and cooling applied to the RT27/ Aluminum foam composite. The first one is a constant flux of *+1800 W/m²* provide at the heated wall of 60min, and then its value becomes negative of the same magnitude for the next *60 min*. The second it's a sin function having the similar area under the curve, it's provide for the same time, Eq. (24**), Figure 7**. In order to study the impact of heat loss at the boundary, thermal insulation from the right-side boundary was removed. Three heat loss coefficients generated by natural convection of the air were investigated (5W/ m², 10W/m² and 15W/m²). **Figure 8** and **Figure 9** present respectively the liquid fraction evolution with constant and sinusoidal cases with and without heat loss. It's can be seen from **Figure 8** and **Figure 9** that the heat losses on the boundary have a greater effect in a sinusoidal heat flux than in the case of constant heat flux and this effect is more important on the solidification than on the melting process of paraffin RT27.

$$q_w = \begin{cases} 1800 W/m^2, (0 \le t \le 60 \text{min}) \\ -1800 W/m^2, (60 < t \le 120 \text{min}) \end{cases}, \quad \text{Constant heating, cooling} \qquad (24)$$

$$q_w = 900 \times \pi \times \sin\left(\pi \times t/60\right), \quad \text{Sinusoidal heating, cooling}$$

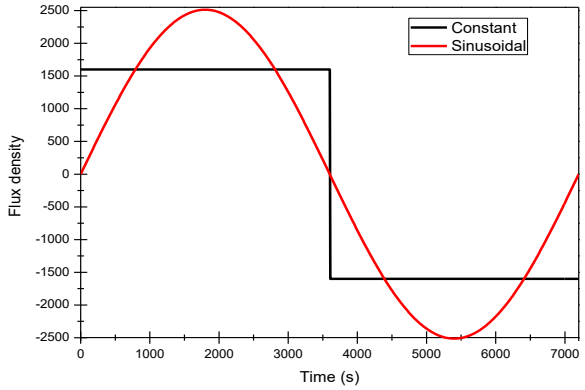
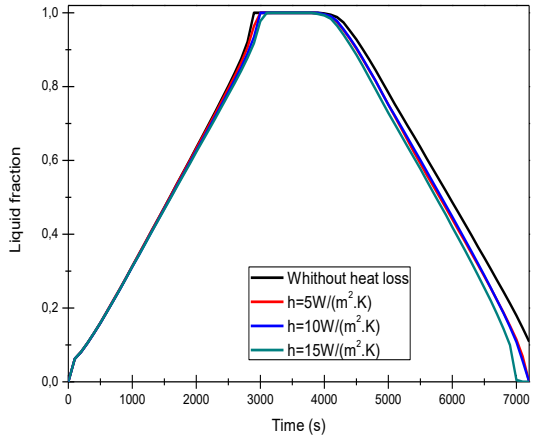


Figure 7. Heating, cooling cycle



(a) (b)

Figure 8. Liquid fraction evolution with and without heat loss, constant case

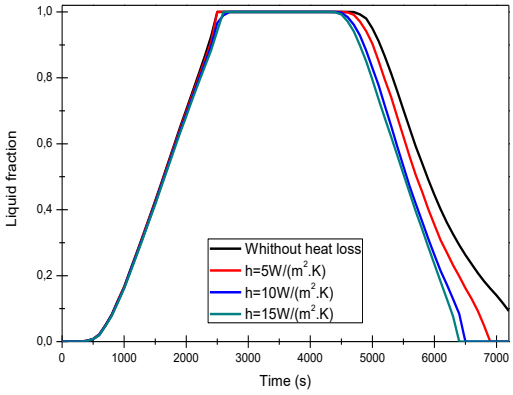


Figure 9. Liquid fraction evolution with and without heat loss, sinusoidal case.

Conclusions

A numerical study is carried out on the solid-liquid and liquid-solid phase change of PCM embedded in metal foam using

COMSOL Mutilphysics 5.3a. A new experimental device was presented. The Brinkmann-Forchheimer extended Darcy equation and the local thermal non-equilibrium model assumption were used by applying a two-energy equation. The phase change is modeled by the entropy-porosity method. The phase change material used its paraffin RT27. The numerical model was validated by comparison with experimental data. It was observed from phase and temperature fields of PCM embedded in metal foam that the conduction is the dominant heat transfer mode during the melting process. It was found that the heat losses on the boundary have a greater effect in a sinusoidal heat flux than in the case of constant heat flux and this effect is more important on the solidification than on the melting process of the paraffin.

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