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Heating and cooling conditions effects on the kinetic of phase change of PCM embedded in metal foam

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Abstract: Phase change materials (PCM) are attractive candidates for energy storage. They can store large quantities of energy in small volumes at nearly constant temperatures. Despite their advantage, their thermal conductivity is very low with a high-volume change during the melting and solidification process. One way to increase their poor thermal conductivity is to embed them into open cell metallic foams. In this paper, a numerical study is conducted on the effect of the heating and cooling conditions on phase change kinetics of paraffin embedded in a metal foam. Constant heating and sinusoidal heating are similarly investigated. For the constant heat flux, a step function ranging from $+1800 \text{ W/m}^2$ to -1800 W/m^2 is considered, while for the variable heat flux, a sinusoidal function having a similar area as step function is considered at one wall of the container to provide heating and cooling of the PCM/ Metal foam composite. A new mathematical model based on the Brinkmann-Forchheimer-extended Darcy equation and the local thermal non-equilibrium model (LTNE) is proposed by applying a two-energy equation. The paraffin phase change is modeled using the enthalpy-porosity method. The numerical results are validated by comparing them with the experimental data. The results showed that at the time of melting it has reduced with sinusoidal heating. The results also showed that the heat losses on the boundary have a greater effect in a sinusoidal heat flux case than in constant heat flux case and this effect is more important on the solidification than on the melting process of the paraffin.

Keywords: Thermal energy storage, numerical simulation, phase change material, metal foam.

C_p	Specific heat capacity, ($J \cdot kg^{-1} \cdot K^{-1}$)	C	Inertial coefficient, ($W \cdot m^{-2} \cdot K^{-1}$)
ρ	Density, (kg/m^3)	K	Permeability, m^2
q	Heat flux	b	Liquid fraction
L_f	Latent heat of fusion (J/kg)	<i>subscripts</i>	
μ	Dynamic viscosity ($Pa \cdot s^{-1}$)	S	Metal foam
t	Time, (s)	w	Hot wall
β	Thermal expansion of PCM, (K^{-1})	f	fluid
T	Temperature, (K)	s	solid
k	Thermal conductivity, ($W/m \cdot K$)	P	Phase change material

1. Introduction

Phase change materials (PCM) offers the possibility to store and release a large amount of heat at the time of phase change in small volumes. They are widely used to improve energy efficiency. [1-2]. However, most PCM have low thermal conductivity, this limit the heat storage efficiency in real applications. [1-3]. Normal paraffin of type C_nH_{2n+2} is an excellent PCM for latent heat storage because of its high latent heat, good stability, and absence of subcooling and toxicity. However, its widespread utilization is hampered by several bottleneck issues. A major drawback is its low thermal conductivity of $0.2\text{--}0.4 \text{ W/(m.K)}$ [4-5], which leads to low heat storage/release rates and low utilization efficiency of the stored energy. PCM thermal conductivity can be enhanced through the addition of materials with high thermal conductivity such as fins [6], porous-graphite [7], nanoparticles [8], and high porosity-metal cells [9-10].

Among these heat transfer enhancers, the high porosity open-cell metal foam is found to be especially effective in improving the performance of PCM because of its high thermal conductivity, large surface area to volume ratio, highly interconnected structure and natural fluid mixing effect. The study of the thermal behavior and transfer mechanisms of PCM/metallic foam composites has attracted increasing research attention. [11-12].

For optimal use of PCM/metal foam composites such as a thermal storage unit or thermal management system, it is necessary to study the effect of the metal foam microstructure (morphology), the thermal conductivity of metal foam, and the heating and cooling condition. These effects studies led to find the vital parameters that can be used to optimize the performance of PCM/metal foam composites for the given application. Various researches have been carried out to study metal foam thermal conductivity and microstructure effects on the effective thermal conductivity of PCM/metal foam composites and phase change kinetics. However, studies are lacking on the effect of the heating and cooling conditions, especially in a continuous process (cyclical heating and cooling). Xia et al. [13] studied the effective thermal conductivity of paraffin/nickel foam composites and paraffin/copper foam composites with high metal foam porosity (>95%). The study was carried out with the effect of porosity on the effective thermal conductivity of paraffin/metal foam composite. The results show that the effective thermal conductivity increases as the porosity decreases. Xiang Huang et al. [14] conducted an experimental study to investigate the thermal conductivity enhancement of myristyl alcohol (MA) by impregnation in metal foam. The MA/metal foam composite was elaborated by vacuum melting infiltration and the impregnation was evaluated by the impregnation ratio, which is the ratio between MA mass and MA theoretical mass. Two types of foam were investigated. The results show that if we compare with the use of pure MA, the use of the copper foam increases the effective thermal conductivity of MA/copper foam by 7.51 times, and the use of nickel foam increased the thermal conductivity by 1.80 times. Sriharsha S. et al [15] carried out a numerical study on the effect of the pores size of aluminum foam on the effective thermal conductivity of paraffin/aluminum foam composites using an analysis of finite elements. To study the effect of the pores size, an aluminum foam with 0.94 porosity and varying pores sizes, from $5\mu\text{m}$ to $100\mu\text{m}$ were considered. It was found that a smaller pore size results in a higher thermal conductivity. On average the thermal conductivity more than doubles, from $5W/(m.K)$ to $12W/(m.K)$, when the pore size is reduced from $100\mu\text{m}$ to $25\mu\text{m}$. El idi [16] studied the effect of metal foam morphology and thermal conductivity effects on the phase change kinetic. The results show that the thermal conductivity plays an essential role in the kinetic phase change of PCM embedded in a metal foam. The melting of PCM embedded in metal foam is almost proportional to the metal foam's thermal conductivity. The melt fraction of PCM embedded in the metal foam increases with the decrease in porosity. The PCM melting and solidification rates for both increase with higher pore density. Small pore density increases permeability and natural convection, and large pore density leads to low permeability that weakens or suppresses natural convection, thus weakening the overall heat transfer. Y. Zhao et al. [17] carried out another numerical study on the effect of porosity and pores density on the melting and solidification cycle. The phase change of PCM in metal foam was modeled by the phase field method. To study the effect of the metal foam structure on the melting and solidification process, four metal foams with the same pore density of 20PPI and different porosity (0.80, 0.85, 0.90 and 0.95) were used. The same methodology was used to study the effect of pore densities. That is to say, four metal foams with the same porosity of 0.9 and different pore densities (5PPI, 10PPI, 20PPI and 40PPI). It was found that the foam morphology (porosity and pore density) play an essential role in the PCM melting and solidification cycle. The melting fraction of PCM embedded in a metal foam increases with the decrease of porosity, and similarly increases with the increase of pore density. S. Abishek et al. [18], studied the microstructure effect on the melting of paraffin in metal foam. The authors were modeling the phase change using the enthalpy-porosity method and used additional volume fraction and field to account for the degree of melting. Furthermore, they used `chtMultiRegionFoam` in OpenFOAM, a conjugate heat transfer and fluid dynamics solver, to simulate the melting process in paraffin aluminum foam composites with a given porosity but varying microstructures. The results show that the specific area, which is the ratio between surface and volume, plays an essential role in the melting of paraffin embedded in the aluminum foam. Recently, Xiaohu Yang et al [19] performed numerical simulation on the phase change kinetic of a novel latent heat thermal energy storage unit filled by metal foams with gradient in pore parameters. The gradients were designed by packaging metal foam blocks with an increase or decrease in porosity or pore density. The metal foam with positive gradient in pore parameters showed a better temperature uniformity. Hence, there is a need to study the cyclic heating and cooling of PCM/ Metal foam composites, which will, in turn, affect the performance of thermal energy storage systems. The study of heating and cooling conditions on the kinetics of phase change will be very interesting and will complete previous studies done in the field.

Among other important applications of PCM, is the use of PCM composites to cool electronic devices that generate a constant heat flux and passive solar energy storage, which is additionally affected by the variation in solar radiation. It is for these reasons that we have chosen to study the constant and sinusoidal heating and cooling. In this paper, we focused on the study of the heating and cooling conditions on the phase change kinetics of paraffin

embedded in aluminum foam and stored energy. The amount of energy stored is directly related to the liquid fraction, and the storage kinetics is related to the temporal evolution of the liquid fraction. For the constant heat flux, a step function ranging from +1800 W/m² to -1800 W/m² is used and for variable heat flux, a sinusoidal function having a similar area as step function was considered at one wall of the container to provide heating and cooling of the PCM/metal foam composite. A new mathematical model is proposed based on the Brinkmann-Forchheimer-extended Darcy equation and the local thermal non-equilibrium model (LTNE) by applying a two-energy equation. The paraffin phase change is modeled by the enthalpy-porosity method. The numerical results are validated by comparing them with the experimental data. The results will be presented and discussed in order to make the optimal use and sizing choice of a thermal energy storage unit for the given application.

properties	Paraffin RT27	Aluminum	Paraffin RT58
Density ($kg.m^{-3}$)	870	2800	850
Heat capacity–solid ($J.K^{-1}.kg^{-1}$)	2400	910	2100
Latent heat ($KJ.kg^{-1}$)	179		181
Melting temperature (K)	300.15		331.15
Dynamic viscosity ($Kg.m^{-1}.s^{-1}$)	3.42×10^{-3}		0.0269
Thermal conductivity –solid ($W.K^{-1}.m^{-1}$)	0.24	237	0.2
Density – liquid ($kg.m^{-3}$)	760		775
Heat capacity –liquid ($J.K^{-1}.kg^{-1}$)	1800		2100
Thermal conductivity – liquid ($W.K^{-1}.m^{-1}$)	0.15		0.2
β (K^{-1})	0.5×10^{-3}		1.1×10^{-4}

Table 1: Thermophysical properties of paraffin RT27, RT58 and aluminum foam.

2. Modeling method

2.1. Physical problem

The physical problem is illustrated in Fig. 1. A square cavity with the dimensions of 4cmx4cm is filled with paraffin wax, RT27, and embedded in an aluminum foam with porosity of 0.93 and pores density of 40PPI. A heat flux is applied in the left wall cavity. There are two types of cycling heating and cooling applied to the PCM/metal foam composite. The first is at a constant flux of +1800 W/m² provided from the heated wall at 60mins, and then its value becomes negative at the same magnitude for the next 60mins. The second, is a sinusoidal function having the similar area under the curve it's provide for the same time, as shown in the Fig. 2. The equation for the boundary condition in the left wall is presented in Eq. (1). The rest of the wall cavity is insulated. Initially, the metal foam and the PCM in the cavity are placed under a uniform melting temperature at 294.15K. The proprieties of paraffin RT27 used for the present study are given in Table1 [20].

$$q_w = \begin{cases} 1800 W/m^2, & (0 \leq t \leq 60 \text{ min}) \\ -1800 W/m^2, & (60 < t \leq 120 \text{ min}) \end{cases}, \quad \text{Constant heating, cooling} \quad (1)$$

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

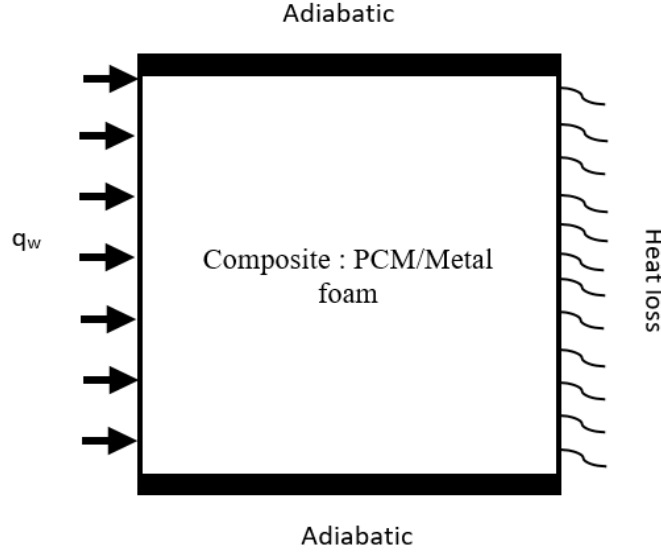


Fig. 1. Physical model

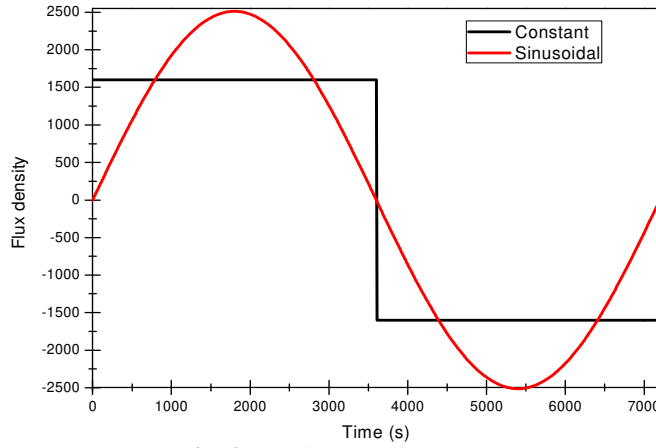


Fig. 2. Heating, cooling cycle

2.2. 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 and solidification
- The metal foam is considered as isotropic and homogeneous.
- The volume expansion is neglected.

2.3. Mathematical model

In the model developed in this paper, a volume-averaging technique is used [21]. Based on the above assumptions, the mathematical model for the present problem can be expressed by the following equations:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

Momentum equations:

$$\frac{\rho_P}{\varepsilon} \frac{\partial u}{\partial t} + \frac{\rho_P}{\varepsilon^2} (\bar{V}\bar{V}) \cdot u = -\frac{\partial p}{\partial x} + \frac{\mu}{\varepsilon} \nabla^2 u - \left(\frac{\mu}{K} + \frac{\rho_P C}{\sqrt{k}} |u| \right) u + S_u \quad (3)$$

$$\frac{\rho_P}{\varepsilon} \frac{\partial v}{\partial t} + \frac{\rho_P}{\varepsilon^2} (\bar{V}\bar{V}) \cdot v = -\frac{\partial p}{\partial y} + \frac{\mu}{\varepsilon} \nabla^2 v - \left(\frac{\mu}{K} + \frac{\rho_P C}{\sqrt{k}} |v| \right) v + S_v + \rho_P g \beta (T - T_{ref}) \quad (4)$$

Where $S_u = A \frac{(1-b)^2}{B^3 + b} u$, 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 [22]. 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:

$$b(T) = \begin{cases} 0 & T < (T_m - \Delta T / 2) \\ \frac{T - T_m + \Delta T / 2}{\Delta T} & (T_m - \frac{\Delta T}{2}) \leq T < (T_m + \frac{\Delta T}{2}) \\ 1 & T > (T_m + \Delta T / 2) \end{cases} \quad (5)$$

The dynamic viscosity is modified by using $S(T) = A \frac{(1-b)^2}{B^3 + b}$ to have an extremely high value when the PCM is at a temperature below its melting temperature.

$$\mu_p(T) = \rho_{pl}(1 + S(T)) \quad (6)$$

There exists a large difference in thermophysical properties between metal foam and PCM saturating [23]. We have two non-equilibrium equations:

Energy equation for PCM:

$$\varepsilon \rho_p C_p \frac{\partial T_f}{\partial \tau} + \rho_p C_p (u \frac{\partial T_p}{\partial x} + v \frac{\partial T_p}{\partial x}) = k_p \nabla^2 T_p + h_{ps} a_{ps} (T_s - T_p) \quad (7)$$

The density variation of PCM can be given by:

$$\rho_p(T) = \rho_{ps} + (\rho_{pl} - \rho_{ps}).b(T) \quad (8)$$

The phase change temperature interval is taken at 3°C [16]. The specific heat of PCM can be written as [24- 25]:

$$C_{pp} = C_{ps} + (C_{pl} - C_{ps}).b(T) + L_f D(T) \quad (9)$$

Where L_f is the latent heat of fusion:

$$D(T) = e^{\left(\frac{-\frac{(T - T_m)^2}{(\Delta T/4)^2}}{\sqrt{\pi} (\Delta T/4)^2} \right)} \quad (10)$$

D is a smoothed Delta Dirac function which is zero everywhere except in the interval [24]. Its integral is equal to 1. The use of this function ensures that the latent heat is conserved during the melting process. The thermal conductivity of PCM can be given as:

$$k_p(T) = k_{ps} + (k_{pl} - k_{ps}).b(T) \quad (11)$$

Energy equation for metal foam:

$$(1 - \varepsilon) \rho_s c_{ps} \frac{\partial T_s}{\partial \tau} = k_s \nabla^2 T_s - h_{ps} a_{ps} (T_s - T_p) \quad (12)$$

Where k_{pe} , k_{se} , h_{ps} are the 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. The following expression was used to estimate h_{ps} [26].

$$h_{ps} = \frac{k_p}{d_f} \left[\left(1 + \frac{4(1 - \varepsilon)}{\varepsilon} \right) + 0.5(1 - \varepsilon)^{0.5} \text{Re}^{0.6} \text{Pr}^{1/3} \right] \quad (13)$$

Many models having been developed to describe effective thermal conductivity. The tetrakaidecahedron cell model proposed by Boomsma and Poulikakos [27] was adopted to describe the thermal conductivity in the present study as shown in the following equations:

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

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

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

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

$$k_{eff} = \frac{\sqrt{2}}{2(R_A + R_B + R_C + R_D)} \quad (18)$$

Where $d = \sqrt{\frac{\sqrt{2}(2 - (5/8)e^3\sqrt{2} - 2\epsilon)}{\pi(3 - 4e\sqrt{2} - e)}}$ and $e=0.339$.

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

$$k_{pe} = k_{eff} | k_s = 0 \quad (19)$$

$$k_{se} = k_{eff} | k_f = 0 \quad (20)$$

3. Thermophysical and structural proprieties of metal foam

Thermophysical proprieties of aluminum foam used in this study are presented in Table 1. Many researches have been carried out to develop an analytical model for predicting permeability and the inertial coefficient of metal foam [28-34]. In this work, we use the model of Calmidi [29] to calculate permeability and the inertial coefficient.

Permeability:

$$K = 0.00073d_p^2(1 - \epsilon)^{-0.224} \left(\frac{d_f}{d_p} \right)^{-1.11} \quad (21)$$

Inertial coefficient:

$$C = 0.00212d_p^2(1 - \epsilon)^{-0.132} \left(\frac{d_f}{d_p} \right)^{-1.63} \quad (22)$$

Where d_f denotes the equivalent diameter of metal foam fibers and d_p pores diameter [29]:

$$\frac{d_f}{d_p} = 1.18 \sqrt{\frac{1 - \epsilon}{\pi}} \left(\frac{1}{1 - e^{-(1 - \epsilon)/0.04}} \right) \quad (23)$$

d_p can be calculate from pore density:

$$d_p = \frac{0.0254}{PPI} \quad (24)$$

The specific area a_{ps} can be calculated by the following formula [30].

$$a_{ps} = \frac{3\pi d_f(1 - e^{-(1 - \epsilon)/0.004})}{(0.59d_p)^2} \quad (25)$$

4. Numerical procedure and model validation

The numerical model is solved by using a finite element analysis with the COMSOL Multiphysics 5.3a software [35]. The numerical model developed in this study was validated by comparing the predicted results with the experimental data of the study by Zhao et al. [36]. In the study conducted by Zhao et al. [36], a copper foam sample with dimensions of 200mm, 120mm and 25mm, pores density of 10PPI, and 95% porosity filled with paraffin wax RT58, was heated with a constant heat of 1600 W/m². The heat loss coefficient generated by the natural convection of air is estimated at about 3W/m². The experimental device developed by Zhao is presented in Fig. 3. The proprieties of

RT58 are given in Table 1. Fig. 4. displays a comparison between the calculated temperature evolutions of the PCM at 8 mm away from the bottom of the copper foam composite and the experimental data. We can observe from the figure that during the melting process, from 1200s to 4000s, there is a small discrepancy between the results of the present model as well as after the melting process. The authors assume that the small difference is mainly due to the estimation of the thermo-physical properties of the RT58 paraffin wax and the heat transfer coefficient used to estimate heat losses and also to the estimation of other thermal and structural properties. It can be concluded that the results obtained by the present model is in accordance with the experimental data on the whole, and the present model is reliable and reasonable.

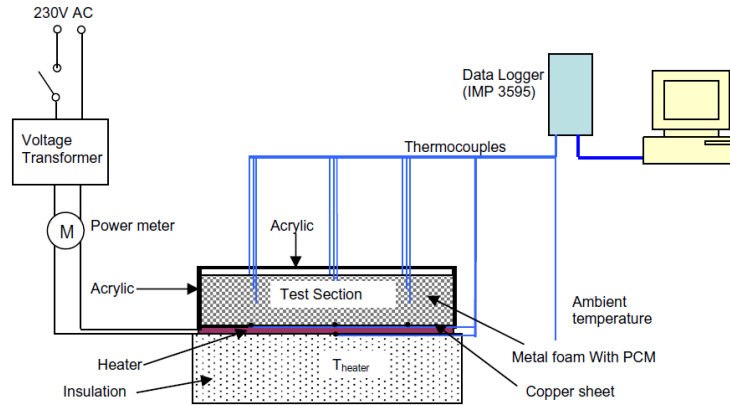


Fig. 3. Experimental device [36]

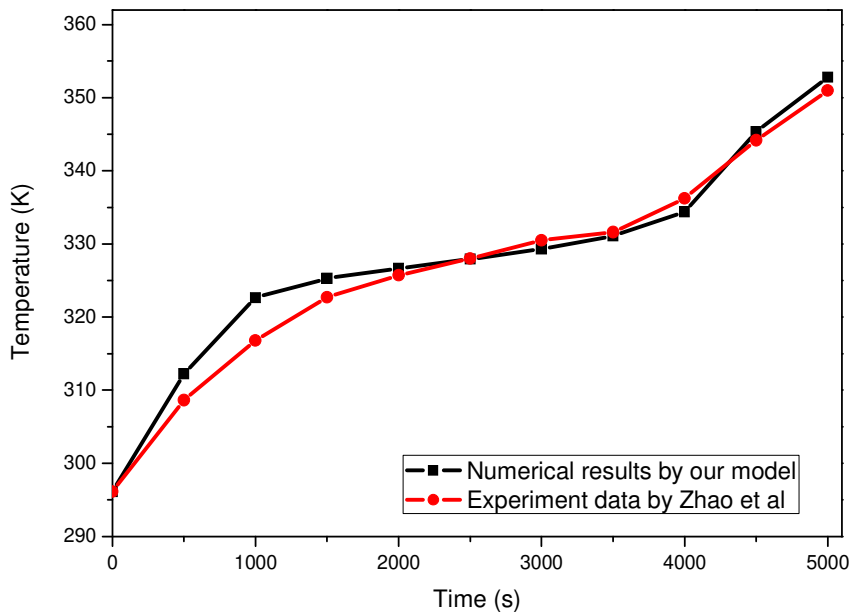


Fig. 4. Comparison between numerical results and literature experiment data.

5. Results and discussion

5.1. Heat supply effect on the kinetics of phase change

The liquid fraction evolution with constant and sinusoidal heat flux is illustrated in Fig. 5. It can be seen from this figure that the melting of paraffin with constant heat flux starts before the melting with sinusoidal heat flux. The melting of paraffin with constant heat flux starts after 40 seconds and starts after about 5mins with variable sinusoidal heat flux. The melt fraction of both becomes the same after 28mins, after which the fraction with variable heat becomes higher as shown in Fig. 5. Then all the paraffin in the aluminum foam becomes liquid (melting fraction equals 1) for heating with sinusoidal heat flux in 41mins and with constant heat flux after 48min. This can be explained by the fact that the behavior of melting fraction evolution is related to the heat supply types. In the constant heat flux case, the heating rate is constant with a magnitude of 1800W/m^2 . Whereas, in the case of heating with sinusoidal heat flux, the heating ratio is zero at the start of the melting process and increases in time in a sinusoidal

manner and reaches its maximum at 30mins, (see Eq (1)). It can be seen that under the same conditions and with the same amount of energy supplied all paraffin filled in an aluminum foam becomes liquid with sinusoidal heating faster than with constant heating. In the solidification process of PCM, the solidification with sinusoidal heating starts 10mins after comparing to the solidification with constant heating after 33minutes we have a same liquid fraction with constant heat flux and sinusoidal heat flux. In the both cases the paraffin is not completely solidified. The fact that the paraffin is not fully solidified can be explained by the fact that the paraffin RT27 has lower thermal conductivity in liquid states (see table 1) which weakens the effective thermal conductivity of the paraffin/foam composite and therefore on the liquid-solid phase change kinetics.

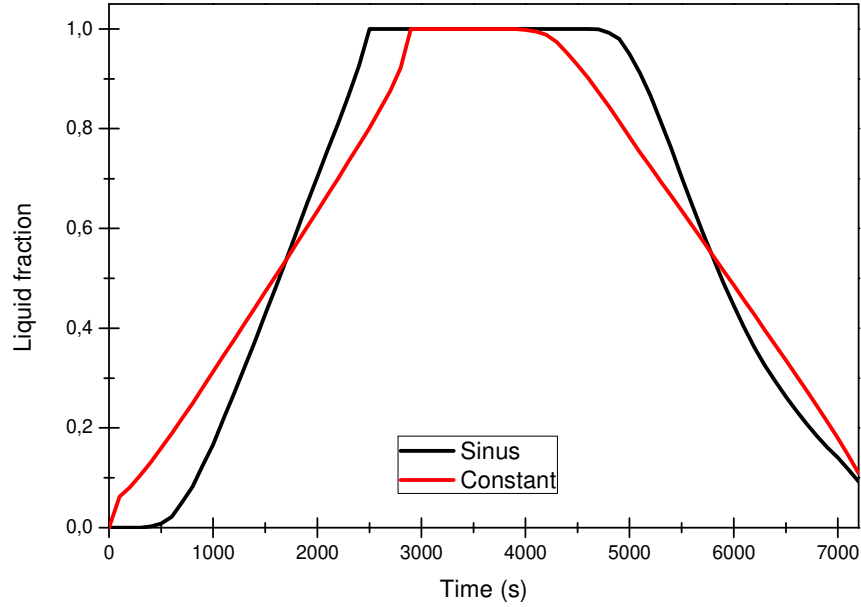


Fig. 5. Liquid fraction during melting and solidification.

5.2. Storage and release of energy

The energy stored in paraffin/aluminum foam composite was calculated for numerical element as:
With $T < T_m$

$$Q_s = \varepsilon \rho_{ps} C_{p_{ps}} (T_p - T_0) + (1 - \varepsilon) \rho_f C_{p_f} (T_s - T_0) \quad (26)$$

With $T = T_m$

$$Q_s = \varepsilon \left[\rho_{ps} C_{p_{ps}} (T_m - T_0) + \frac{\rho_{ps} + \rho_{pl}}{2} L_F \right] + (1 - \varepsilon) \rho_f C_{p_f} (T_m - T_0) \quad (27)$$

With $T > T_m$

$$Q_s = \varepsilon \left[\rho_{ps} C_{p_{ps}} (T_m - T_0) + \frac{\rho_{ps} + \rho_{pl}}{2} L_F + \rho_{pl} C_{p_{pl}} (T_p - T_m) \right] + (1 - \varepsilon) \rho_f C_{p_f} (T_s - T_0) \quad (28)$$

The energy stored is then calculated by integrating the right expression for the energy over the volume for each of the elements, resulting in a total amount of energy stored in the entire volume. The energy stored during melting and solidification of paraffin is shown in Fig. 6.

At the initial stage of melting the stored energy in paraffin / aluminum foam with constant heating is higher than compared to variable heating due to the corresponding heater heating rate. It is also noted that the amount of energy stored and is not released at the same period of time. This can be explained by that the paraffin in the liquid state has a lower thermal conductivity than in the solid state and therefore the thermal transfer is less intense during the solidification process than during melting. This result is very interesting for sizing PCM/ Metal foam to be used as thermal energy storage unit. A such result will necessarily lead to an accumulation of heat in the PCM/ Metal foam composite and therefore an increase of temperature. After several cycles the temperature of the PCM/ Metal foam composite can be reached at a temperature higher than the temperature of melting of PCM at the beginning of the heating. This means that there is loss of storage by latent heat which is the reason why we use the PCM.

Heat loss coefficient	5 W/(m ² .K)	10 W/(m ² .K)	15 W/(m ² .K)
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Constant heat flux	7200 seconds	7200 seconds	7100 seconds
Sinusoidal heat flux	6900 seconds	6500 seconds	6400 seconds

Table 2: Solidification time

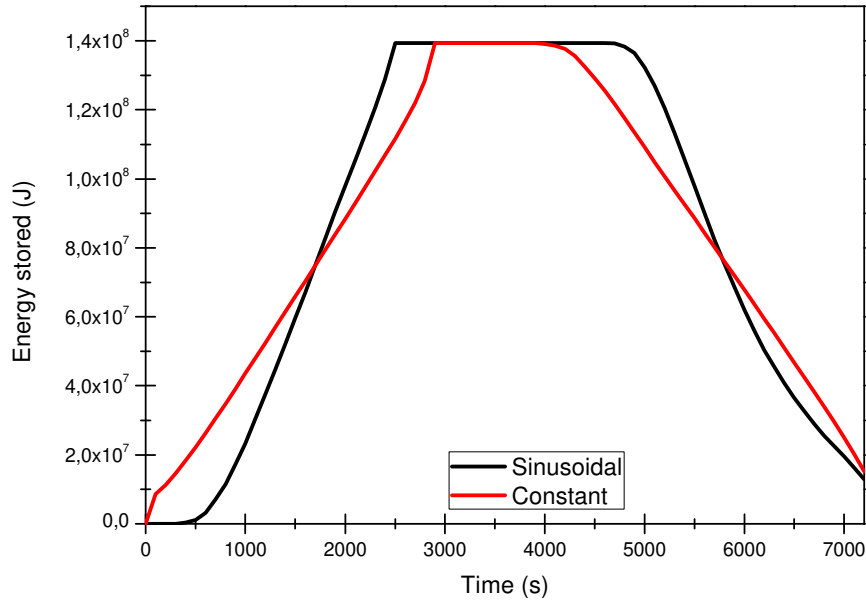


Fig. 6. Thermal energy stored and discharge.

5.3. Heat loss effect

In order to study the effect of heat loss at the boundary, thermal insulation from the right-side boundary was removed. The environment temperature is 294.15K. Three heat loss coefficients generated by natural convection of the air were investigated (5W/m^2 , 10W/m^2 and 15W/m^2). Fig. 7 (a). presents the liquid fraction evolution with heat loss compared to the liquid fraction without heat loss in the right boundary with constant heating. Fig. 7 (b). illustrates the same process with sinusoidal heating. The result shows that for the melting process with constant heating as well as with sinusoidal heating, a weak effect of heat loss took place by natural convection of air in the right boundary. Also, there was a larger effect on the solidification process in comparison to the melting process. At first, the average temperature of the paraffin/aluminum foam composite is equal to the environment temperature, and therefore the right wall too. The heat loss in the right boundary is zero and increases with time until it reaches the maximum temperature value. In contrast, during the solidification process the temperature is at its maximum at the beginning and decreases with a slower rate than the increase rate as the thermal conductivity of the paraffin is lower at the liquid state than at solid state. All this leads to a greater convective heat flux during the solidification process than during the fusion process. Therefore, the heat losses are more important during the solidification cycle than the melting cycle. The full solidification time of paraffin for the cases with heat losses was summarized in Table 2. We can deduce from Fig. 8, Fig. 7(b). and table 2 that the heat losses have a greater impact on the solidification processes in the case of sinusoidal cooling than in constant cooling case. This is due to the fact that the heat transfer rate is constant in the case of constant heat flux.. Whereas, in the case of sinusoidal heat flux, the heat transfer rate is zero at the start of solidification and increases with the time in a sinusoidal manner before reaching its maximum value at 30mins, Eq (1). Therefore, in the sinusoidal heat flux case, the right wall will keep its maximum temperature for a longer period than in the case of constant heat flux. As seen earlier, the amount of stored energy depends on the liquid fraction. This led to deduce that the heat losses from the right wall have a greater effect in the case of a sinusoidal heat flux than in the case of constant heat flux. Moreover, this effect is more important on the solidification process than on the melting process of the paraffin.

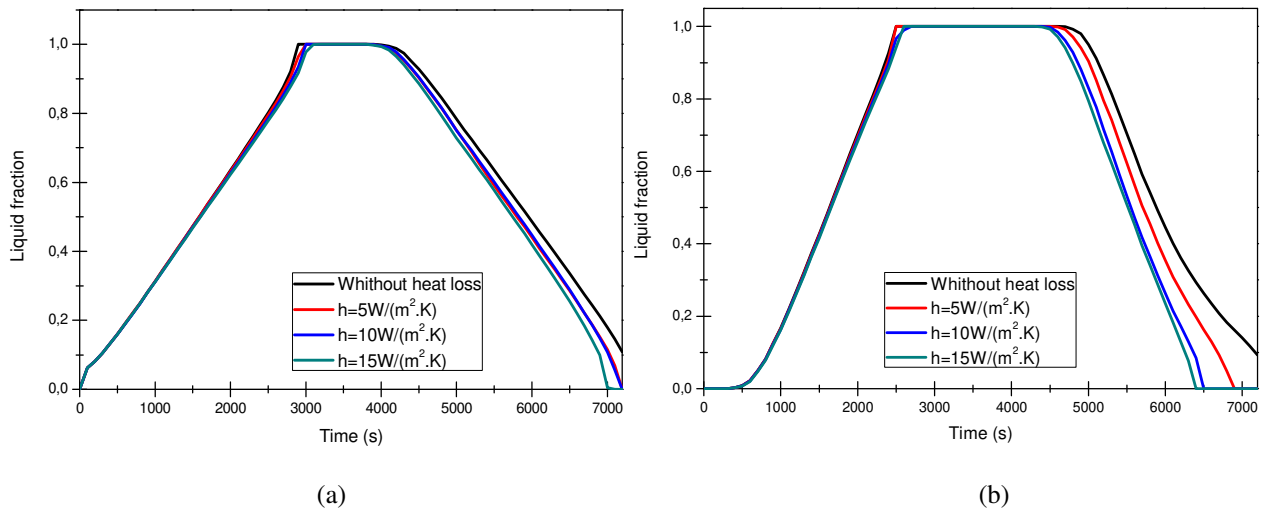


Fig. 7. Liquid fraction evolution with and without heat loss: (a) constant, (b) sinusoidal

6. Conclusion

A numerical study was carried out on the energy supply efficiency of cyclical heating and cooling. The Brinkmann-Forchheimer-extended Darcy equation and the local thermal non-equilibrium model assumption were used due to the larger difference in thermal properties between the metal foam and the PCM. The phase change is modeled by the enthalpy-porosity method. The phase change material used paraffin RT27. The numerical model was developed and validated by comparison with experimental data coming from the literature. The heating and cooling conditions of the phase change kinetic of paraffin embedded in aluminum foam and stored energy was carried out. It was discovered that with sinusoidal heating the initial melting rate is low and becomes higher after some time. Furthermore, it was showed that with sinusoidal heating the melting time of PCM filled in a metal foam is reduce compared to when it was subject to a constant heating and the same behavior during the solidification cycle. The results also show 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.

Future studies will aim to find the best compromise between foam proprieties, heat supply, energy storage density and time of the storage process.

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