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Numerical simulation of thermal energy storage with phase change materials in aluminum foam

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Abstract

A numerical investigation on a latent heat thermal energy storage system based on a PCM is accomplished. The PCM used is paraffin wax having a melting process over a range of temperature and a high value of latent heat. A metal foam is employed to improve the thermal conductivity of the PCM. The geometry of the system under investigation is an enclosure with foam and tubes. The internal surface of the tubes are assumed at a constant temperature above the melting temperature of the PCM to simulate the heat transfer from a hot fluid. The external surfaces of the enclosure are assumed adiabatic or with heat losses toward the external ambient. The phase change of PCM is modelled with the enthalpy-porosity theory while the metal foam is modelled like a porous media using the Darcy-Forchheimer law. Local thermal non-equilibrium (LTNE) model is assumed. The results are presented in term of melting time and temperature field for the charging process. Different porosities are investigated at an assigned pore per inch (PPI). The presence of metal foam reduces the melting time more than one order of magnitude. The model can be further enlarged to simulate different types of metal foam or PCM.

Thermal Energy Storage, TES, LHTES, PCM, Metal Foam, Solar energy

1. Introduction

The objective of CO₂ reduction or the dependence of the developed Countries from fossil energy has led to an increase of interest in developing renewable energy sources. Storage of energy is fundamental in order to provide the supply of energy in a continuous way. A technological enhancement is indispensable to develop an appropriate thermal energy storage system (TES) in order to resolve the intermittence of solar energy. A TES is a storage media [1] useful to accumulate the thermal energy during the excess of energy and release it when necessary. Mainly TES systems can be classified in three types [1]: sensible heat thermal energy storage system (SHTESS), latent heat thermal energy storage system (LHTESS) and

chemical heat storage energy system (CHSES). The benefits of a LHTESS are the quasi-constant temperature during the storing [2], complete reversibility of charging/discharging cycle and chemical stability. The most interesting phase change process is solid to liquid process given that it presents average characteristics between the solid to solid process and liquid to gas process. Henceforth the materials giving rise a solid-liquid phase change process are called phase change materials (PCMs). They have a small variation of volume during the phase change and an high value of latent heat [3], indispensable to store a large quantity of heat. The PCM used in this work is organic paraffin, a very common material, cheap, abundant in nature and not corrosive [4]. The principal drawback of LHTESS is the small value of the thermal conductivity of the paraffin PCM. Ameliorative techniques are essential to optimize the thermal storage system such as the addition of highly-conductive nanoparticles [5], metallic inclusion [6], carbon inclusion [7] or metal foam insertion [8].

In this study an open-cell metal foam is used to enhance the thermal conductivity of the whole system. The LHTESS system is optimized using the highly-conductive material for the metal foam and a PCM with high latent heat. Harikrishnan et al. [9] experimentally investigated the paraffin with nanomaterials for solar heating system. Zhao et al. [10] numerically analysed a high-temperature latent heat thermal energy storage system for concentrated solar power plants using phase change material with graphite foam. Xiao et al. [11] experimentally studied the effective thermal conductivity of a PCM paraffin with an open-cell metal foam inside a test chamber in order to understand the thermal behaviour of the combination pcm/metal foam. A computational study on metal foam and PCM was accomplished by Nithyanandam and Pitchumani [12]. The domain was a rectangular array of tubes filled of PCM with or without metal foam for different parameters of the foam. The enthalpy porosity method was utilized in [13] to design the solidification and melting of a PCM inside a metal foam. A numerical investigation on a LHTESS system for solar application is accomplished in Yang et al. [14]. An experimental investigation is made by Zhou et al [15], where the PCM in metal foam is heated for charging process and then it is cooled for discharging process. A similar experimental study was made in [16] where a copper foam with the paraffin wax RT58 are employed for low-temperature storage application. Chen et al. [17] experimentally and numerically studied the melting of phase change material in metal foam at pore scale. A comparison between microscopic and macroscopic approaches was made by Hu et al [18], where the microscopic approaches was used to obtain the thermal conductivity and the interstitial heat transfer coefficient. The cylindrical domain of a LHTESS system using paraffin wax and metal foam was numerically and experimentally studied in [19] for different porosity. The results showed a good agreement between the experimental data and the numerical results. Tao et al. [20] numerically

investigated a composite PCM/metal foam at varying PPI and porosity. A numerical study to understand the effects of the variation along the vertical direction of the metal foam porosity was accomplished in [21]. Chen et al. [22] studied a paraffin-integrated solar collector with aluminum foam in numerical way.

After this short review, in this work a numerical investigation on LHTESS based on a PCM is accomplished. The geometry is an enclosure between two cylindrical concentric tubes. For modeling the metal foam, the Darcy-Forchheimer model is employed and the enthalpy-porosity method models the melting of the paraffin. Local thermal non-equilibrium model is assumed for the interaction energy between the PCM and metal foam. The results are presented in terms of total melting time, temperature evolution for various porosity and assigned pore per inch (PPI).

2. Physical and numerical models

First, The physical model consists in two concentric shell tubes with inner and outer radius equal respectively 2 mm and 12 mm. The Length of the tubes are 100 mm and they are arranged in vertical way. In the inner tube flows the heat transfer fluid (HTF) that exchanges heat with the PCM enclosed between the outer shell tube and inner tube as in fig.1.

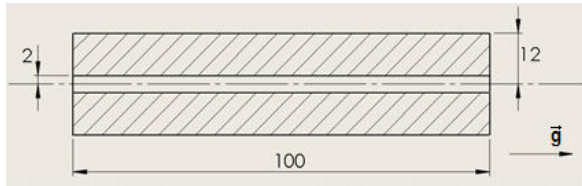


Fig.1 Physical model of the LHTESS.

The computational domain is two-dimensional and the axial symmetry is assumed. Moreover, two configurations are considered, configuration A and configuration B. The configuration A (fig.2a) has the inner surface at constant temperature equals to 350 K to simulate the heat exchange between the HTF and the system, while the other surfaces are adiabatic. The configuration B (fig.2b) has the same conditions but the outer surface is at constant temperature equals to 300 K. The simulation of melting PCM is modelled with enthalpy-porosity method [23]. In this method the solid-liquid surface is not explicitly traced but there is a mixed solid-liquid region where the solid phase and liquid phase are not clearly separable. This zone is modelled as a “pseudo” porous zone where a new parameter is defined.

This parameter is called “liquid fraction” and it represents the ratio between the liquid phase part of a representative volume and the total volume. Therefore, the mixed region is defined in a range of temperature between $T_{solidus}$ and $T_{liquidus}$. $T_{solidus}$ is the temperature below which the PCM is fully solid and $T_{liquidus}$ is the temperature upper which the PCM is fully

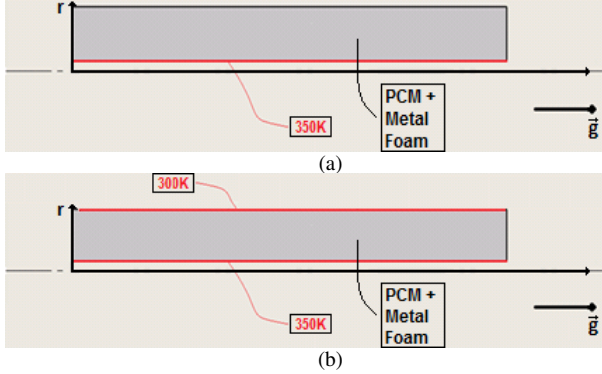


Fig.2: The two configurations with different boundary conditions for the outer surface: (a) adiabatic and (b) isothermal.

liquid. The value of the liquid fraction, β , is then:

$$\left\{ \begin{array}{ll} \beta = 0 & \text{for } T < T_{solidus} \\ \beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & \text{for } T_{solidus} < T < T_{liquidus} \\ \beta = 1 & \text{for } T > T_{liquidus} \end{array} \right. \quad (1)$$

where T is the local temperature. Moreover the solid phase zone is modelled in the mixed region with a added source term in the momentum equation. The metal foam is modelled like a porous medium, therefore, the pressure drop is taken into account by an another source term in the momentum equation. For the energy interaction between the PCM and the metal foam, the local thermal non-equilibrium model is employed [13]. This model considers the metal foam and the PCM separated and not in thermal equilibrium. Thus, two energy equations are necessary, one for the PCM and the other for the metal foam. The governing equations are:

$$\nabla \cdot (\rho \vec{V}) = 0 \quad (2)$$

$$\rho \left(\frac{\partial \vec{V}}{\partial t} + (\nabla \cdot \vec{V}) \vec{V} \right) = \mu (\nabla^2 \vec{V}) - \nabla p + \vec{S} \quad (3)$$

for PCM the energy equation is:

$$\varepsilon \rho_{pcm} c_{pcm} \frac{DT_{pcm}}{Dt} = k_{pcm,eff} \nabla^2 T_{pcm} + h_{sf} \alpha_{sf} (T_{pcm} - T_m) - \varepsilon \rho_{pcm} H_L \frac{\partial \beta}{\partial t} \quad (4)$$

and for the metal foam is:

$$(1-\varepsilon)\rho_m c_m \frac{DT_m}{Dt} = k_{m,eff} \nabla^2 T_m + h_{sf} \alpha_{sf} (T_m - T_{pcm}) \quad (5)$$

where \vec{V} is the velocity of the PCM in liquid phase, ρ and μ are respectively the density and the viscosity of the PCM, p is the pressure, the vector \vec{S} represent a global source term given by the following equation:

$$\vec{S} = \frac{(1-\beta)^2}{(\beta^3 + \pi)^3} A_{mush} \vec{V} + \frac{\mu}{K} \vec{V} + \frac{C_F}{\sqrt{K}} \rho \vec{V} |\vec{V}| + \rho \vec{g} \gamma (T - T_0) \quad (6)$$

The first term on the right side models the presence of the solid part in the mixed region called Carman-Koseny term where β is the liquid fraction, the number 0.001 is necessary to avoid division by zero [12], A_{mush} is the mushy zone constant that acts as a damping factor of the velocity during the solidification[23]. Its value does not affect the melting rate of the PCM with the metal foam and it sets to 10^5 kg/m³s. The second and third term are the Darcy-Forchheimer terms where K is the permeability of the porous metal foam media and C_F is inertial drag factor. The last term is the Boussinesq approximation, essential to simulate the natural convection in the PCM. The vector \vec{g} is the gravitational acceleration, T_0 is the operating temperature and γ is the thermal expansion coefficient. The permeability K and the inertial drag factor C_F are calculated with the following [24]:

$$K = 0.00073(1-\varepsilon)^{-0.224} \left(\frac{d_f}{d_p} \right)^{-1.11} d_p^2 \quad (7)$$

$$C_F = 0.00212(1-\varepsilon)^{-0.132} \left(\frac{d_f}{d_p} \right)^{-1.63} \quad (8)$$

d_f and d_p are respectively the ligament diameter and the pore diameter of the metal foam. they are linked to the other parameter of the metal foam through the following equations [24]:

$$\frac{d_f}{d_p} = 1.18 \sqrt{\frac{1-\varepsilon}{3\pi}} \left(\frac{1}{1 - e^{1(1-\varepsilon)/0.04}} \right), \quad d_p = \frac{0.0224}{\omega} \quad (9)$$

where ω is the pore density that represents the number of pores across one linear inch. In the energy equations, ε is the porosity of the metal foam and the subscripts “m” and “pcm” refer respectively to the properties of the metal

foam and the properties of the PCM. $k_{\text{pcm,eff}}$ and $k_{\text{m,eff}}$ are, respectively, the effective thermal conductivity of the PCM and metal foam. The calculation of these parameters is described in Boomsma et al. [25] and are not reported here for brevity. H_L is the latent heat of the PCM and t is the time. The energy interaction between PCM and metal foam is represented by the product $h_{\text{sf}} \alpha_{\text{sf}}$, h_{sf} is the interstitial local heat transfer coefficient, α_{sf} is the surface area density of the metal foam that represent the whole contact between PCM and metal foam. For the present study α_{sf} and h_{sf} are calculated by means of the equations given in [26], with the local Reynolds number referred to ligament diameter:

$$Re_d = \frac{\rho V d_f}{\mu}, \alpha_{\text{sf}} = \frac{3\pi d_f}{(0.59 d_p)^2} \left(1 - e^{-\frac{1(1-\varepsilon)}{0.04}}\right), h_{\text{sf}} = a Re_d^b Pr_{\text{pcm}}^{0.37} \left(\frac{k_f}{d_f}\right) \quad (10)$$

with $a=0.76$ and $b=0.4$ for $1 \leq Re_d < 40$, $a=0.52$ and $b=0.5$ for $40 \leq Re_d < 1000$, $a=0.26$ and $b=0.6$ for $1000 \leq Re_d < 2 \times 10^5$.

The materials chosen are paraffin RT58 as PCM and aluminum for the metal foam [27]. In the table 1 are listed the properties of the materials.

The finite volume method is employed to solve the governing equations. A transient method is used and the time step size is set to 0.05s. The second order upwind scheme is chosen to discretize the momentum and energy equations. The SIMPLE algorithm is employed in pressure-velocity coupling. The values of the minimum residual to convergence are fixed at 10^{-5} for the continuity and momentum equations and 10^{-8} for the energy equation. The software employed is Ansys Fluent and a user-define function is implemented to connect the Reynolds number and the local interstitial heat transfer. The mesh is composed of quadrilateral cells and it is denser near the wall and thin in the middle of the domain. Six different meshes are compared in order to have a independent solution from the numerical mesh. The results suggest that a mesh with 20×50 cell nodes is a good choice because it represents the best compromise between the numerical accuracy of the solution and the computational cost. The model is then validated via to a comparison with the work of Krishnan et al.[28]. The same characteristics

Table 1. Thermal proprieties of the materials

Thermal properties	Paraffin RT58	Metal foam
Density [kg/m^3]	840	2719
Specific Heat [$\text{J}/\text{kg K}$]	2100	871
Thermal Conductivity [$\text{W} / \text{m K}$]	0.2	202.4
Dynamic Viscosity [$\text{kg}/\text{m s}$]	0.0269	-
Thermal expansion coefficient [$1/\text{K}$]	0.00011	-
Melting Heat [J / kg]	180000	-
Solidus Temperature [K]	321	-
Liquidus Temperature [K]	335	-

are used and the two models present similar results, therefore there is a good agreement between them.

3. Results and Discussions

The results are evaluated for different porosity values ϵ equal to 0.80 and, 0.90 at an assigned PPI value equal to 20 for both configurations. The LTNE model is assumed. In all cases the temperature of the internal cylindrical wall is assumed constant and equal to 350 K. A comparison in terms of liquid fraction and temperature field is made. In Fig. 3 are showed the evolution of melting of both configurations for a CLEAN case without foam at different time values (30 s, 300 s, 900 s, 2500 s). The red zone is the liquid phase while the blue zone is the solid phase. The other colors represent the mushy zone. The melting rate is very low due to the small value of thermal conductivity of pure PCM, in fact at 2500 s the PCM is not totally liquid both for configuration A and configuration B. In particular, in the configuration B the melting rate is slower due to the heat losses. The shape of melting zone is sloped because of the effect of the natural convection.

In Fig. 4 the temperature fields are reported for both configurations at the same instants of time (30 s, 300 s, 900 s, 2500 s). The paths are similar to the previous figure. The average values of liquid fraction and temperature of the system as functions of time are shown in Fig. 5 for both configuration. Obviously in the configuration B the steady state temperature is lower respect to the configuration A due to the heat losses and therefore the average liquid fraction of B is inferior respect to the configuration A. It is important to see that the growth of the temperature up to the steady state is very smooth.

An important evaluation is made in Fig. 6 because it compares the pure PCM with the PCM/metal foam for the configuration A in term of average liquid fraction and temperature. The metal foam considered has a porosity equals to 80%. The difference between the pure paraffin and the PCM/metal

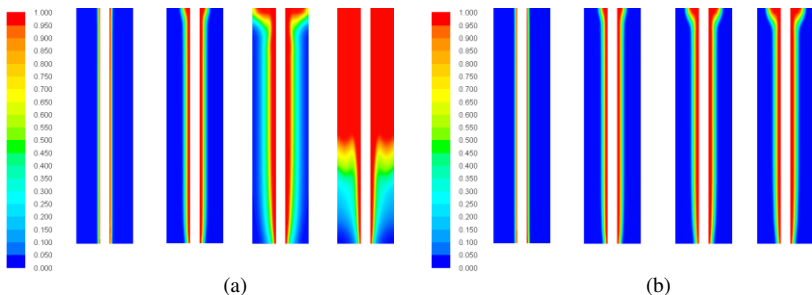


Fig.3 Melting zone for (a) configuration A and (b) configuration B without metal foam at different time values (30 s, 300 s, 900 s, 2500 s).

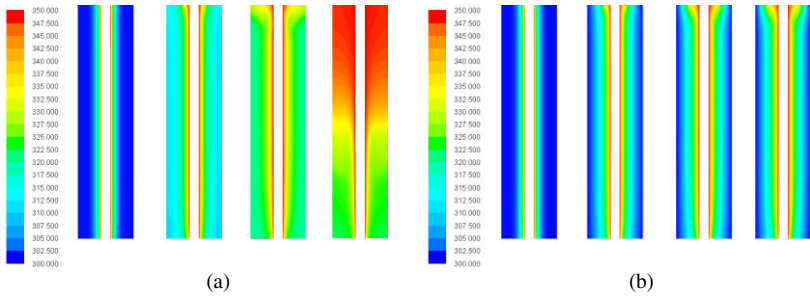


Fig.4 Temperature fields for (a) configuration A and (b) configuration B without metal foam at different time values (30 s, 300 s, 900 s, 2500 s).

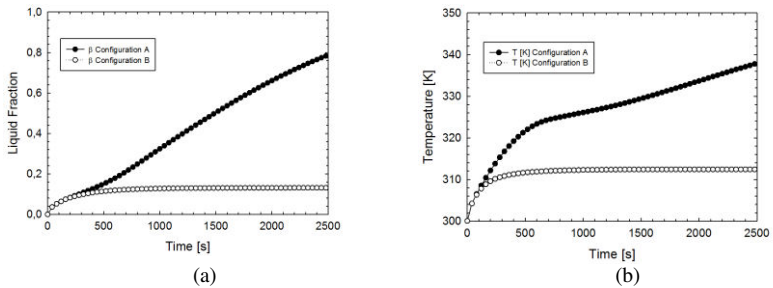


Fig.5 Average liquid fraction (a) and average temperature (b) as functions of the time for both configuration.

foam is evident, in fact the presence of the foam improves significantly the heat transfer and thus the melting rate even more an order of magnitude, hence is required the log-scale of the time. For example the time of melting for the pcm with metal foam at 80% of porosity is equals to 17.5s while for the clean case is over 2500 s. Finally in Fig.7 the effect of the porosity is evaluated only for the configuration A, given that the configuration B has the

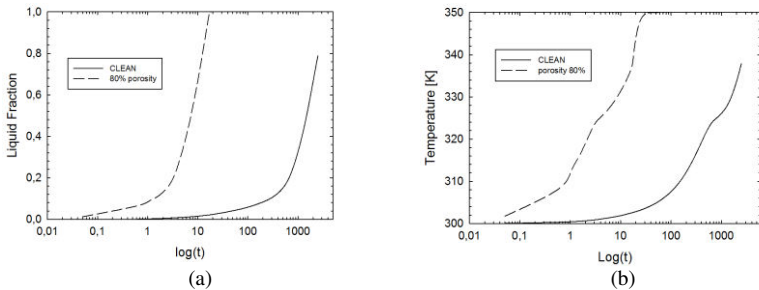


Fig.6 pure PCM versus PCM/ metal foam at 80% of porosity in term of evolution of liquid fraction (a) and the average temperature (b) of the domain for configuration A.

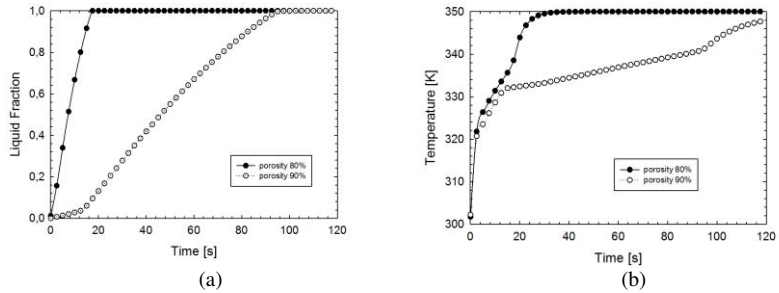


Fig.7 Average liquid fraction (a) and average temperature (b) at varying of porosity for the configuration A.

same behavior but with lower values of the average thermal properties. This figure analyzes the effect of the porosity on the melting rate and average evolution of temperature. The order of magnitude of the melting time for both porosities is similar but at 90% the rate of melting is slower. Therefore higher values of porosity decrease the rate of melting, in fact the melting time at 90% of porosity is 94s.

4. Conclusion

A numerical investigation on the latent heat thermal energy stored system was accomplished. The PCM is pure paraffin wax and the metal foam is aluminum. The enthalpy-porosity theory was employed to simulate the phase change process. The metal foam was modelled with the Darcy-Forchheimer law. The LTNE model was used. The results showed that the presence of the metal foam improves significantly the thermal performance of the system, in fact there is a huge reduction of the melting time more than one order of magnitude. Moreover the effect of the porosity was studied and it can observe that the reduction of the porosity determined an increase of the melting rate.

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