

Numerical investigation on Nano-PCM in aluminum foam in latent thermal energy storages

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ABSTRACT

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Thermal storage system (TES) with phase change material (PCM) is an important device to store thermal energy. It works such a thermal buffer to reconcile the supply energy with the energy demand. It has a wide application field especially for solar thermal energy storage. The main drawback is the low value of thermal conductivity of the PCM making the system useless for the thermal engineering applications. A way to resolve this problem is to combine the PCM with a highly conductive material like metal foam and/or nanoparticles. In this paper a numerical investigation on the metal foam effects into the latent heat thermal energy storage system, based on a phase change material with nanoparticles (Nano-PCM), is accomplished. The modelled TES is a typical 70L water tank filled up with Nano-PCM with pipes to transfer thermal energy from a fluid to the Nano-PCM. The PCM is a pure paraffin wax and the nanoparticles are in aluminum oxide. The metal foam is made of aluminum with assigned values of porosity. The enthalpy-porosity theory is employed to simulate the phase change of the Nano-PCM and the metal foam is modelled as a porous media.

Numerical simulations are carried out using the Ansys-Fluent code. The results are shown in term of melting time, temperature at varying of time and total amount of stored energy.

1. INTRODUCTION

A Thermal Energy Storage (TES) [1] is a device capable to store exceed energy by heating a storage medium. In base of the medium material, a TES could be classified as a sensible TES and a Latent TES. The latter one has the best performance because it permits to store exceed energy at quasi-constant temperature. The base material of a Latent TES is the Phase Change Material (PCM) that during the phase change process, adsorbs and then releases the thermal energy with a small volume variation [2]. There are many types of PCM in literature [3], in particular, for a solid-liquid phase change process, the paraffin [4] has many advantages such as high latent heat, non-toxicity, chemical stability, small volume variation but one of the worst drawbacks is the low value of thermal conductivity, making the application of pure PCM counterproductive for thermal storage application because it could behavior as an insulated material. Therefore, different enhancement techniques are recommended in order to improve the paraffin thermal conductivity as putting highly-conductive nanoparticles [5] to the pure PCM or employing metal foam [6]. The addition of nanoparticles in the PCM creates a new class of material, called Nano-PCM [7]. In the literature there are few works about Nano-PCM, for example Shin and Banerjee [7], have conducted some experimental works for enhancing the heat capacity of the PCM with the addition of nanoparticles. Chieruzzi et al. [8] have experimentally investigated a PCM with nanoparticles concluding that the latent heat of the Nano-PCM has increased of 12%. Ercole et al. [9] have found a robust correlation of the specific heat varying of temperature, nanoparticles diameters and volume concentration for PCM molten salt with Silica nanoparticles

using experimental data in literature. Bayat et al. [10] numerically simulated the performance of a finned heat sink with phase change material with nanoparticles. By the results, they showed that the Nano-PCM has better performance even with low concentration of nanoparticles while for higher concentrations it seems that the heat sink has lower thermal performance. The applications of enhanced technique for PCM, especially using metal foam, have been broadly investigated in literature [11]. For example, Siahpush et al. [12] have performed both in numerical and experimental way a study on a thermal energy storage system with PCM and metal foam assuming the Local Thermal Equilibrium hypothesis to simulate the heat transfer between PCM and metal foam. Tian and Zhao [13] have numerically investigated a TES system with a paraffin RT58 as PCM with aluminum metal foam assuming the Local Thermal Non-Equilibrium model. Fang et al. [14] has proposed an index to characterize the effective energy storage capacity of a TES system with PCM. The works of Nano-PCM in metal foam, Hossain et al [15] have studied a numerical model with PCM with copper oxide nanoparticles in metal foam. The local thermal equilibrium is assumed between the PCM and the metal foam while the Darcy model is employed without the Forchheimer extension. The authors have demonstrated that the Nano-PCM melts at a faster rate inside the metal foam. Mahdi and Nsofor [16] experimentally worked on a Triplex-tube storage system with Nano-PCM in metal foam and they conclude that the metal foam has a predominant role in conduction phenomenon respect to the convection of liquid PCM and the nanoparticles slightly reduce the convection role but they do not eliminate it. Ren et al. [17] have numerically investigate the melting process of the PCM of a TES system with nanoparticles and

metal foam using the boundary-lattice Boltzmann method at pore-scale. The results have showed that the metal foam is more effective respect to the nanoparticles for the improvement of the PCM melting rate.

This work numerically studies the Nano-PCM inside a metal foam. The volume concentration of Nano-PCM is 1% of Al_2O_3 inside a paraffin wax with a melting point around $58^\circ C$. A single-phase model is applied to evaluate the thermophysical properties of the Nano-PCM. The metal foam is aluminum and the assigned porosity is set to 80%. The porous media assumption is considered to study the metal foam and the Local Thermal Non-Equilibrium hypothesis is applied to evaluate the heat transfer between the Nano-PCM and the metal foam. The system is a typical 70L water tank filled up with Nano-PCM with metal foam. The charging process is monitored in term of liquid fraction, average temperature evolution and stored energy.

2. PHYSICAL MODEL

The physical model of the TES system is a parallelepiped with the dimension of $785 \times 120 \times 710$ mm filled with Nano-PCM and a number of pipes, where the HTF flows, pass throughout it. For the thermal and geometry symmetry the computational domain is only a part of the system and it is showed in fig.1. On the pipe surface is imposed a Temperature T_w to 343.15 K in order to simulate the heat transfer between the Heat Transfer Fluid and the system during the charging operation. The other surfaces are assumed adiabatic. Along the y-axis a gravitational acceleration is imposed and the Boussinesq approximation is considered to take into account the natural convection. The enthalpy-porosity method is employed [18], because the paraffin melts in a temperature range. In this method it is introduced a non-dimensional parameter, called liquid fraction, indicated with Greek letter β , that describes the mixed zone during the phase change.

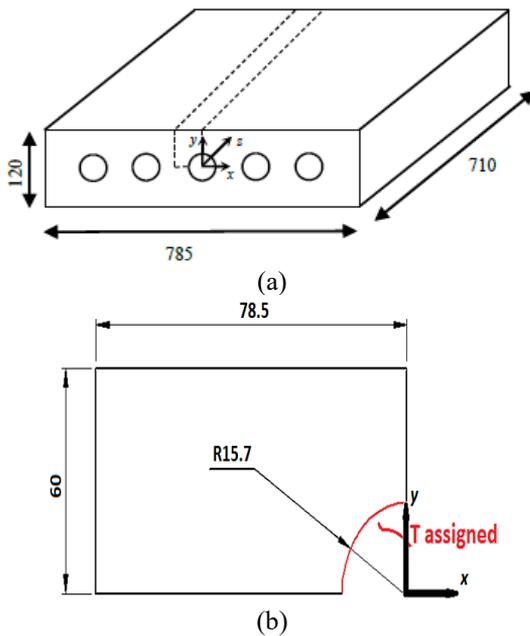


Figure 1. Physical model of TES system. The dotted lines (a) represent the computational domain, frontal view of the computational domain (b)

This parameter is ranged from 0 to 1:

$$\beta = \begin{cases} 0 & (T < T_{SOLIDUS}) \\ \frac{T - T_{SOLIDUS}}{T_{LIQUIDUS} - T_{SOLIDUS}} & (T_{SOLIDUS} < T < T_{LIQUIDUS}) \\ 1 & (T > T_{LIQUIDUS}) \end{cases} \quad (1)$$

T is the local temperature, $T_{liquidus}$ is the temperature over which the PCM is fully liquid while $T_{solidus}$ is the temperature under which it is fully solid. The mixed zone exists in a range of temperature between $T_{liquidus}$ and $T_{solidus}$.

The metal foam is modelled as a porous media subject to the Brinkman extended Darcy-Forchheimer model, therefore, a source term is added in the momentum equation. To simulate the heat transfer between PCM and metal foam, the Local Thermal Non-Equilibrium (LTNE) assumption is applied, where there are two function of temperature in the porous media, one for the fluid phase (PCM) and the other for the solid phase (metal foam).

A single-phase approach is assumed to model the interaction between the nanoparticles and the PCM in the liquid phase. This approach considers the Nano-PCM as a homogeneous fluid where the difference of velocity between the nanoparticles and pure PCM is neglected, so the thermophysical properties of the Nano-PCM are a weighted average respect to the volume concentration ψ between the property's values of the nanoparticles and the pure PCM. The volume concentration of the Nano-PCM ψ represents the ratio between the volume of the nanoparticles and the total volume of the domain:

$$\psi = \frac{Vol_{Al_2O_3}}{Vol_{TOTAL}} \quad (2)$$

To simulate the natural convection in the PCM/Nano-PCM a Boussinesq approximation is considered:

$$\rho_{PCM} = \rho_0 [1 - \gamma (T_{PCM} - T_0)] \quad (3)$$

where ρ_{PCM} and T_{PCM} are respectively the density and the temperature of the PCM, ρ_0 and T_0 are the operating density and temperature and γ is the thermal expansion coefficient. The operating temperature T_0 is equal to 321 K.

The governing equation [19] are the following:

$$\nabla \cdot (\rho \vec{V}) = 0 \quad (4)$$

$$\frac{\rho}{\varepsilon} \left(\frac{\partial \vec{V}}{\partial t} + \frac{(\nabla \cdot \vec{V})}{\varepsilon} \vec{V} \right) = \frac{\mu_{PCM}}{\varepsilon} (\nabla^2 \vec{V}) - \nabla p + \vec{S} \quad (5)$$

In local thermal non-equilibrium model the equation of energy for PCM is [20]:

$$\varepsilon \rho_{PCM} c_{PCM} \frac{DT_{PCM}}{Dt} = k_{PCM} \nabla^2 T_{PCM} + \alpha_{sf} h_{sf} (T_{PCM} - T_{foam}) - \varepsilon \rho_{PCM} H_L \frac{\partial \beta}{\partial t} \quad (6)$$

While for the metal foam is [20]:

$$(1 - \varepsilon)\rho_{foam}c_{foam} \frac{\partial T_{foam}}{\partial t} = k_{Foam} \nabla^2 T_{foam} + \alpha_{sf} h_{sf} (T_{foam} - T_{PCM}) \quad (7)$$

V is the velocity of the liquid PCM or Nano-PCM, t is the time, μ_{PCM} is the viscosity of the PCM or Nano-PCM; p is the relative pressure, S is an addition term necessary to include the Boussinesq approximation, the mushy zone and the porous zone:

$$\vec{S} = \rho \vec{g} \gamma (T - T_0) + \left[\frac{(1 - \beta)^2}{(\beta^3 + 0.001)^3} A_{mush} + \frac{\mu}{K} + \frac{C_F}{\sqrt{K}} \rho |\vec{V}| \right] \vec{V} \quad (8)$$

Therefore, the first term is the Boussinesq approximation, the second term models the mushy zone where A_{mush} is the mushy zone constant which represents the damping of the velocity to zero during the solidification [19]. In these simulations the value of mushy zone constant is set to 10^5 Kg/m³s. The third and fourth terms model the porous media, K is the permeability of the porous media and C_F is inertial drag factor. The permeability and drag factor values are calculated with the following relations, by Calmidi et al. [21]:

$$K = 0.00073(1 - \varepsilon)^{-0.224} \left(\frac{d_f}{d_p} \right)^{-1.11} d_p^2 \quad (9)$$

$$C_F = .00212(1 - \varepsilon)^{-0.132} \left(\frac{d_f}{d_p} \right)^{-1.63} \quad (10)$$

ρ and c are respectively the density and specific heat, ε is the porosity of the metal foam, k is the thermal conductivity, H_L is the latent heat of the PCM. The subscript _{PCM} indicates the physical characteristic of the PCM or Nano-PCM, while the subscript _{foam} indicates the physical characteristic of the metal foam. To calculate the values of the properties of the Nano-PCM, the following relations [22] are used:

$$\rho_{NANOPCM} = (1 - \psi)\rho_{wax} + \psi\rho_{Al_2O_3} \quad (11)$$

$$(\rho c)_{NANOPCM} = (1 - \psi)(\rho c)_{wax} + \psi(\rho c)_{Al_2O_3} \quad (12)$$

$$(\rho \gamma)_{NANOPCM} = (1 - \psi)(\rho \gamma)_{wax} \quad (13)$$

where the subscript _{NANOPCM} indicates the physical characteristic of the Nano-PCM, the subscript _{wax} indicates the physical characteristic of pure paraffin wax, the subscript _{Al₂O₃} indicates the physical characteristic of the material of the nanoparticles (aluminum oxide). ψ is the volume fraction of

the Nano-PCM. The viscosity is calculated by [22]:

$$\mu_{NANOPCM} = \frac{\mu_{wax}}{(1 - \psi)^{2.5}} \quad (14)$$

The thermal conductivity is calculated from the Maxwell equation [23]:

$$\frac{k_{NANOPCM}}{k_{wax}} = \frac{k_{Al_2O_3} + 2k_{wax} - 2\psi(k_{wax} - k_{Al_2O_3})}{k_{Al_2O_3} + 2k_{wax} + \psi(k_{wax} - k_{Al_2O_3})} \quad (15)$$

The latent heat of the Nano-PCM is evaluated using [24]:

$$(H_L)_{NANOPCM} = \frac{(1 - \psi) * (\rho H_L)_{wax}}{\rho_{NANOPCM}} \quad (16)$$

The melting temperature is the same for all of three types of material. The pure PCM is the paraffin RT58 purchased from Rubitherm technologies GmbH [25]. The nanoparticles are made of oxide aluminum (Al₂O₃). The Nano-PCMs considered have a volume fraction equal to 1%. The metal foam is made of aluminum with a porosity value of 80%. All the thermal properties are expressed in table 2.

Table 2. Thermal properties of the materials

	RT58	Al ₂ O ₃	Al	Nano-PCM
ρ [kg/m ³]	840	3980	2719	871.4
c [J/kg K]	2100	850	871	2042.9
k [W/ m K]	0.2	35	202.4	0.206
μ [kg/m s]	0.0269	-	-	0.0276
γ [1/K]	1.10e-4	-	-	1.05e-4
H_L [J/kg]	180000	-	-	171779
$T_{solidus}$ [K]	321	-	-	321
$T_{liquidus}$ [K]	335	-	-	335

3. NUMERICAL MODEL

The finite volume approach using Ansys Fluent code is employed for the simulations. The SIMPLE algorithm is employed for the pressure-velocity coupling; PRESTO algorithm is used for the pressure calculation. A transient analysis is performed with a time step size is equal to 0.5 s. The convergence errors are assumed equals to 10^{-5} , for continuity and momentum equation, and 10^{-8} , for energy equation. The boundary conditions and initial condition are:

Pipe Surface: Assigned temperature T_w at 343.15K.

The other surfaces are adiabatic.

Initial condition:

The system is assumed to be at 300K

For the mesh independence solution three different meshes were tested with different nodes 27630 nodes, 51322 nodes, 104556 nodes and the mesh with 27630 nodes was chosen because it represents the best compromise between the computational costs and accuracy. In table 1 is represented the independence mesh test.

The model has been validated using the work of Krishnan et al. [26]. The comparison has showed a good agreement between this model and the model of Krishnan et al.

Table 1. Independence mesh test

% difference	27630 cells	51322 cells	104556 cells
27630 cells	0	0.7	1.2
51322 cells	0.7	0	5
104556 cells	1.2	5	0

4. RESULTS AND DISCUSSIONS

In fig.2 there is a comparison in term of average liquid fraction and average temperature of pure PCM and Nano-PCM at 1% during the time it can be seen that the improvement of the nanoparticles has a small influence on the melting process, because the two curve are nearly overlapped. The melting time is above 40000 s and there is a smooth transition from solid to liquid phase during the time. In figure 3 there is a comparison between the various improvement in term of liquid fraction. The first important consideration is about the log scale of time, because when the metal foam is added, the melting process is very fast in comparison of PCM or Nano-PCM. This can be explained by the fact that the metal foam has a thermal conductivity bigger than PCM of at least two order of magnitude, leading a fast propagation of heat inside the whole system reaching every point of the PCM thanks to its foam structure. In figure 4 is possible to see the temperature evolution of Pure PCM, only Nano-PCM without metal foam, and the temperature evolution of Nano-PCM in metal foam and the metal foam temperature.

The melting time of Nano-PCM with Metal foam is about 2000 s. With the addition of metal foam, even that the melting time is very low, nevertheless the stored energy is lower and after the reaching of the thermal equilibrium the stored energy is constant.

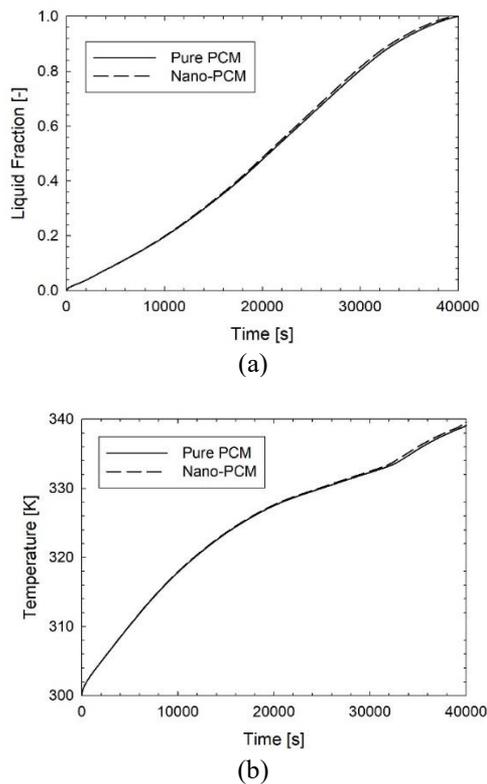


Figure 2. Comparison of pure PCM and Nano-PCM at 1% during the time in term of (a) average liquid fraction and (b) average temperature evolution

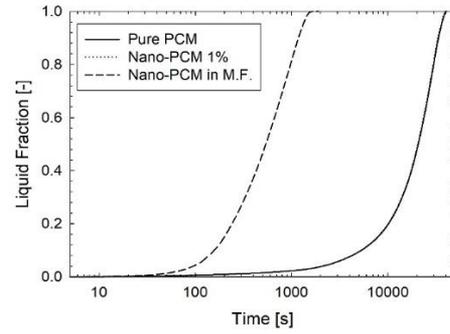


Figure 3. Average liquid fraction evolution during the time for pure PCM, nano-PCM and nano-PCM in metal foam

Where the metal foam is not inserted, the temperature evolution curves are overlapped. In presence of metal foam, the Nano-PCM melts very fast, its melting time is nearly 2000 s. The evolution temperature curves of nano-PCM in metal foam and of metal foam reduce their temperature difference during the time until the whole nano-PCM is completely melted. Moreover, there is a shape change of the curves at about 330 K, because around that temperature the majority part of the domain is melting maintaining the temperature nearly constant. In figure 5 is represented the average stored energy per unit of mass. With the pure PCM it is possible to store more energy, while adding nanoparticles leads to a slightly lower stored energy. In figure 6 there is the total stored energy per unit of mass during the time for pure PCM, Nano-PCM and Nano-PCM in metal foam.

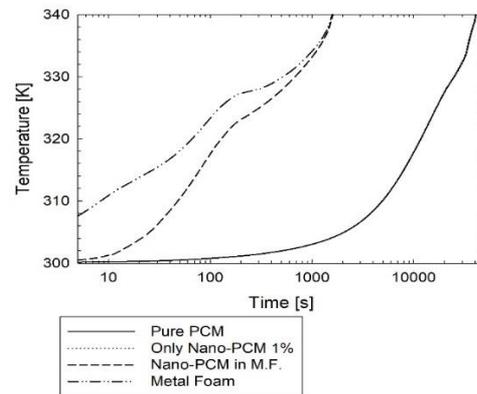


Figure 4. Average temperature evolution during the time for pure PCM, nano-PCM, nano-PCM in metal foam and metal foam

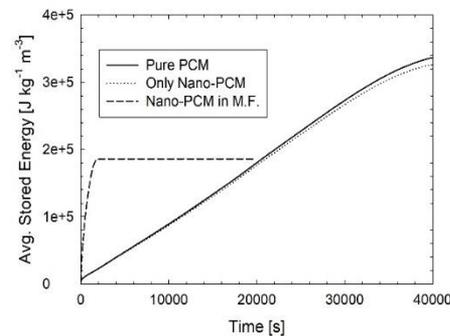


Figure 5. Average stored energy per unit of mass evolution during the time for pure PCM, nano-PCM, nano-PCM in metal foam

5. CONCLUSIONS

A numerical investigation on the metal foam effects into the latent heat thermal energy storage system, based on a phase change material with nanoparticles (Nano-PCM), has been accomplished. The modelled TES was a typical 70L water tank filled up with Nano-PCM and the metal foam. The results have showed that the metal foam is more effective than the nano-PCM in term of melting rate. About the stored energy, the amount of stored energy is minor when the metal foam is applied.

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NOMENCLATURE

A_{mush}	Mushy constant $\text{kg. m}^{-3}\text{s}^{-1}$
C_F	drag factor coefficient
c	specific heat, $\text{J. kg}^{-1}. \text{K}^{-1}$
d_f	fiber diameter, m
d_p	pore diameter, m
h_{sf}	interfacial heat transf. coeff. $\text{W. m}^{-2}. \text{K}^{-1}$
H_L	Latent Heat J. kg^{-1}
k	thermal conductivity, $\text{W. m}^{-1}. \text{K}^{-1}$
K	porous permeability, m^2
p	relative pressure, Pa
Pr	Prandtl number
r	radius tube, m
Re	Reynolds number
S	Source Term N. m^{-3}
T	Time s
T	Temperature, K
Vol	Volume
V	velocity, m s^{-1}
x	cartesian axis direction, m
y	cartesian axis direction, m
z	cartesian axis direction, m

Greek symbols

α_{sf}	specific surface area density, m^{-1}
B	Liquid fraction
ε	porosity
γ	Thermal expansion coefficient K^{-1}
μ	dynamic viscosity, $\text{kg. m}^{-1}\text{s}^{-1}$
ρ	density, kg. m^{-3}
ψ	Volume concentration of nanoparticles
ω	number of pores per inch, m^{-1}

Subscripts

0	operating condition
df	fiber diameter
eff	effective
$Foam$	Metal foam
$Liquidus$	Liquidus temperature
$NANOPCM$	Nano-enhanced PCM
PCM	Phase change material
$Solidus$	Solidus temperature
$TOTAL$	Whole domain