Numerical study on latent thermal energy storages with PCM partially filled with aluminium foam

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Abstract. A numerical investigation on the effects of the metal foam into the Latent Heat Thermal Energy Storage System, based on a phase change material, is accomplished. The geometry of the system is a rectangular box heated from below. The PCM is completely embedded in the rectangular box, it is pure paraffin wax with a low value of thermal conductivity and it melts in a range of temperatures. The metal foam is made of copper and it partially fills the rectangular box in order to understand the optimal filling ratio of the foam to have the better thermal performance. The enthalpy-porosity theory is employed to simulate the phase change of the PCM and the metal foam is modelled as a porous media that follow the Brinkman-extended Darcy model. The results are shown in term of melting time, temperature and energy at varying of time or at varying the filling height ratio.

1. Introduction
The energy thermal demand has the natural characteristic to be variable both in temporal term and in the methods of use. This variation makes difficult to match the energy demand with the energy supply, so it is important to build a thermal buffer to solve this problem and to improve the efficiency of the entire thermal energy system for various applications. A solution could be the Thermal Energy Store (TES) [1]. It is a device that works as a thermal buffer in order to avoid losing of exceed energy. There are many types of thermal storage system (TES) among which the latent heat thermal energy storage systems (LHTESS) with phase change material (PCM) that represent the best choice because they work at nearly constant temperature, they are stable and they have an high energy density. The Phase Change Materials (PCMs) have the peculiarity to change their phase from solid to liquid and vice-versa during the heat transfer maintaining the operating temperature at near the melting temperature. There are many type of PCM, organic, inorganic, metal alloys etc, but the most usable PCM for thermal storage system in low temperatures is the organic paraffin. It is not corrosive, it is chemically stable, the phase change is reversible and the latent heat is very high [2]. Nevertheless the main disadvantage of the PCM is the low value of thermal conductivity, making the melting time and the solidification time very long respect to a working cycle of charge of the system. Therefore, some solution are proposed in literature, such as the usage of metal foam [3] or finned tubes [4]. Particularly, the open-cell metal foam represents the best solutions because it has a very high ratio between the area of heat exchange and its volume and the base material has high value of thermal conductivity. Some studies in literature have been accomplished, Yang et al. [5] presented a transient mathematical model to study the influence of the porosity variation on the thermal behavior of a system based on PCM, numerically. The results indicate that with the varying porosity there is a...
beneficial effect on the melting rate. Xiao et al [6] experimentally study the thermal behaviour between the PCM paraffin and open-cell metal foam for latent heat storage. Two type of metal foam are employed, copper and nickel with high value of porosity. They found that the copper foam is better than the nickel foam in term of heat exchange, because the effective thermal conductivity is faster for the copper foam than the nickel foam. It is worth to investigate the influence of the metal foam for not fully covered PCM because the PCM has a non-zero volume change during the melting. Some studies are accomplished to understand the filling ratio of metal foam inside the PCM, for example a two dimensional axisymmetric numerical model of PCM during the melting process in a partial thermal storage system has been analysed in Archibold et al [7]. The enthalpy-porosity method has been employed and the effects of Grashof and Stefan number have been analysed. By the results, the increment of the Grashof number enhances the heat transfer and when the Stefan number increases at constant Grashof number there is a faster melting rate. An experimental test on transient performance of a phase change material (PCM)-based heat sink filled with a copper foam has been accomplished by Zhu et al [8]. The aim has to understand the influence of the filling height ratio of the copper foam on the system. Moreover, the authors have investigated the effects of pore size and heating power. By the results they have founded that the filling height ratio might improve the thermal performance linearly. An investigation on PCM-TES with porous media at different filling ratio has been investigated in Xu et al. [9]. A new parameter has been defined to understand the melting performance and TES capacity. By the results the optimal filling height ratio is 0.7 because in this case the performance parameter is higher respect to clean case without the porous media.

In this paper a numerical investigation on the effects of the metal foam into the Latent Heat Thermal Energy Storage System, based on a phase change material, is accomplished. The geometry of the system is a rectangular box heated from below. The PCM is completely embedded in the rectangular box. The metal foam is made of copper and it partially fills the rectangular box in order to understand the optimal filling ratio of the foam to have the better thermal performance.. The results are shown in term of melting time, temperature and energy at varying of time or at varying the filling height ratio for charging phase.

2. Physical model
The model for the LHTESS consists in an rectangular box filled up with Pure PCM embedded with metal foam. The mathematical domain is 2D with a total height $H$ equals to 20 mm and the base $B$ equals to 75 mm. At bottom of domain, a heat flux is applied. The metal foam could completely occupies the domain, or a part of domain, therefore a filling height ratio $R$ is defined:

$$R = \frac{h_{mf}}{H}$$

Where $h_{mf}$ is the height of the metal foam inside the domain while $H$ is the total height of the domain. In this work $R$ is 0 - pure PCM -, 1/3, 2/3 and 1 - domain is fully occupied by the metal foam -. The other surfaces are adiabatic. The fig.1 illustrates the domain and the boundary conditions. The melting phenomenon of the PCM can be modelled with the enthalpy-porosity method [10], in which the solid-liquid interface is not explicitly traced but the method defines a mixed solid-liquid region that is described as a “pseudo” porous zone where the porosity is the liquid fraction.

![Mathematical model of the LHTESS.](image)

Fig.1 Mathematical model of the LHTESS.
The most important parameter of the enthalpy-porosity method is the liquid fraction, indicated with Greek letter $\beta$. The value is 0 when the zone is fully solid, 1 when it is fully liquid and between 0 to 1 in the mixed region:

$$
\begin{align*}
\beta &= 0 & \text{for } & T < T_{\text{solidus}} \\
\beta &= \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} & \text{for } & T_{\text{solidus}} < T < T_{\text{liquidus}} \\
\beta &= 1 & \text{for } & T > T_{\text{liquidus}}
\end{align*}
$$

(2)

$T$ is the local temperature of the cell, $T_{\text{liquidus}}$ is the temperature upper which the domain is completely liquid and $T_{\text{solidus}}$ is the temperature below which it is completely solid. The similitude of the mixed region with a porous region is justify by the fact that when the liquid fraction tends to zero, the mixed region is solidifying and the velocity of the PCM tends to slow down, in fact the solid part of the mixed zone is modelled by adding a source term in the momentum equation. The metal foam is modelled with the Brinkman-extended Darcy-Forchheimer model because it behaves like a porous media; therefore another source term is used in the momentum equation to simulate its presence. The gravitational acceleration is along the $y$-axis and the Boussinesq approximation is considered in order to take into account the buoyancy force due to natural convection.

The governing equation are the following:

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

(3)

$$
\rho \frac{D\vec{V}}{Dt} = \mu_{\text{PCM}} \left( \nabla^2 \vec{V} \right) - \nabla p + \rho g \gamma (T - T_0) \hat{j} + \left( \frac{(1-\beta)^2}{\beta^3 + 0.001} \right) A_{\text{mushy}} + \frac{\mu}{K} \sqrt{K} \rho |\vec{V}| \vec{V}
$$

(4)

$$
\left( (1-\varepsilon) \rho_{\text{mf}} c_{\text{mf}} + \varepsilon \rho_{\text{pcm}} c_{\text{pcm}} \right) \frac{DT}{Dt} = k_{\text{eff}} \nabla^2 T - \varepsilon \rho_{\text{pcm}} H_L \frac{\partial \beta}{\partial t}
$$

(5)

Where $\vec{V}$ is the velocity vector of the PCM in liquid phase, $t$ is the time, $\mu$, $\rho$ and $T$ are respectively the viscosity, density and the temperature, $p$ the relative pressure, $g$ the gravity acceleration module, $\gamma$ is the PCM thermal expansion coefficient according to Boussinesq equation where $T_0$ is the operating temperature, set to 310K. The first term in the square brackets is the Kozeny–Carman term that models the presence of the solid part in the mixed region during the melting, where the small number (0.001) avoids the division by zero when $\beta$ is null. $A_{\text{mushy}}$ is the mushy zone constant which takes into account the damping of the velocity during the solidification [11]. Its value is set to $10^5$ kg/(m$^3$ s) and it does not affect the rate of melting with the presence of the metal foam. The Darcy term and the Forchheimer term of the porous media are respectively the second and third term inside the square brackets in equation 4, where $K$ is the permeability and $C_F$ is inertial drag factor. Their values are calculated with the following relations [12]:

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

(6)

$$
C_F = 0.00212 (1-\varepsilon)^{-1.132} \left( \frac{d_f}{d_p} \right)^{-1.63}
$$

(7)

$d_f$ is the ligament diameter of the metal foam, $d_p$ is the pore diameter. These physical characteristics are related each other by means of the following relations [12]:

3
\[ \frac{d_r}{d_p} = 1.18 \frac{1}{3\pi} \left( \frac{1}{1 - e^{(1 - \varepsilon)/0.04}} \right) \]

\[ d_p = \frac{0.0224}{\omega} \]

(8)

\( \omega \) is the pore density of the metal foam that represents the number of pores across one inch. In this study the pore size is assigned at 15 Pore Per Inch (PPI). The heat transfer interaction between the metal foam and the PCM is governed by the Local thermal Equilibrium Assumption therefore the local temperature between PCM and metal foam is equal, so a unique Local Temperature function \( T \) in the equation (5) is defined. In equation (5) \( \rho_{mf} \) and \( c_{mf} \) are respectively the density and specific heat of the metal foam, \( \varepsilon \) is the porosity of the metal foam and its value is set to 0.80 and \( c_{pcm} \) is the specific heat of PCM. \( k_{eff} \) is the effective thermal conductivity calculated as weighted average between PCM and metal foam with the porosity:

\[ k_{eff} = (1 - \varepsilon) k_{mf} + \varepsilon k_{pcm} \]

(9)

where \( k_{mf} \) and \( k_{pcm} \) are respectively the thermal conductivities of metal foam and PCM. \( H_L \) is the latent heat of the PCM. The PCM in this study is the RT42 paraffin, the metal foam is made by copper with a density of 8978 kg/m\(^3\), thermal conductivity of 387.6 W/mK and a specific heat of 381 W/kg K. The properties of the PCM are listed in table 1. In this study the properties are assumed constant, except for the PCM density, the copper foam is isotropic and homogenous.

Table 1. Physical properties for the paraffin wax

| Physical properties       | Paraffin RT42 [13] |
|---------------------------|--------------------|
| Density [kg/m\(^3\)]     | 840                |
| Specific Heat [J/kg K]    | 2100               |
| Thermal Conductivity [W / m K] | 0.2               |
| Dynamic Viscosity [kg/m s] | 0.0269            |
| Thermal expansion coefficient [1/K] | 0.00011    |
| Melting Heat [J / kg]     | 180000             |
| Solidus Temperature [K]   | 321                |
| Liquidus Temperature [K]  | 335                |

The boundary conditions are reported in the following:

- At \( y=0 \) and \( 0 \leq x \leq 25 \): adiabatic condition.
- At \( y=0 \) and \( 25 < x \leq 50 \): applied heat flux \( q=12600 \) W/m\(^2\).
- At \( y=0 \) and \( 50 < x \leq 75 \): adiabatic condition.
- For \( y=20 \) and \( 0 \leq x \leq 75 \): adiabatic condition.
- For \( x=0 \) and \( 0 \leq y \leq 20 \): adiabatic condition.
- For \( x=75 \) and \( 0 \leq y \leq 20 \): adiabatic condition.
3. Numerical model

The finite volume method [14] is employed for resolving the governing equation (3), (4), (5) using the commercial code Ansys Fluent [15]. The SIMPLE algorithm is applied for coupling the pressure and the velocity; for the spatial discretization the gradient evaluation is based on green-gauss cell; Linear method is used for pressure calculation and the second order upwind scheme is utilized for momentum and energy equation. The residual convergence values are imposed to 10^{-4} for continuity equation and momentum equation while 10^{-6} is set to energy equation. A transient mode is enabled with a time step size equals to 0.1 s. The employed grid is a set of quadrilateral control volumes with a finer grid in the separation edge between the metal foam and the pure PCM at correspondence of y=h. Therefore 3 different meshes are used for this study, a simple rectangular mesh for R=0 and R=1 and other two meshes for R=2/3 and R=1/3. After some tests, the mesh with R=1/3 seems more instable respect to the other height filling ratio, therefore a study to obtain a solution independent from the mesh is made with four different grids at R=1/3: 789 cells, 3840 cells, 7540 cells, 15633 cells. The mesh with 3840 cells represents the best mesh grid for the present study because the computational costs are satisfactory with the accuracy.

4. Results and discussion

In fig.2 there are the average evolution of temperature and liquid fraction for each filling height ratio.

![Fig.2 Average Temperature evolution (a) and average liquid fraction (b) as function of time for different filling height ratio.](image)

The shape of the curves changing with the R ratio and when the liquid fraction is 1, then the Temperature evolution is the same for each R ratio. Moreover, at beginning, the liquid fraction evolution is lowered, but when the temperature is near the melting temperature then the liquid fraction curves has a great increment. The melting time is different for different R values, it is about 1000 s for R=1 and it is 1400 s at R=0. At these time, it is possible to see the variation of shape for the Avg. Temperature curve. About the energy, in fig.3 it is possible to see that there are very few differences with the variation of height filling ratio and further studies are necessary to fully understand the stored energy inside the system.
Finally, in Fig. 4 the surface average bottom temperature is plotted as function of time and it can be seen that for the case without metal foam (R=0) there is a spike of temperature, because, at beginning, the PCM has a low value of thermal conductivity and therefore it behaves as a thermal insulator; but when the melting starts, the natural convection in the PCM begins and it is responsible to take the heat from the bottom lowering the bottom temperature.

5. Conclusions
A numerical investigation on the effects of the metal foam into the Latent Heat Thermal Energy Storage System, based on a phase change material, is accomplished. The geometry of the system is a rectangular box heated from below. The PCM is completely embedded in the rectangular box, it is pure paraffin wax with a low value of thermal conductivity and it melts in a range of temperatures. The metal foam is made of copper and it partially fills the rectangular box in order to understand the optimal filling ratio of the foam to have the better thermal performance. The results have showed that the melting time changing with the filling ratio but the energy is constant while for the temperature the presence of the metal foam lowers the temperature, especially in the beginning avoiding heat spikes.
6. References

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