Numerical investigation on thermal behaviors of two-dimensional latent thermal energy storage with PCM and aluminum foam

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Abstract. A numerical investigation on Latent Heat Thermal Energy Storage System (LHTESS) based on a phase change material (PCM) is accomplished. The PCM is a pure paraffin wax with a low thermal conductivity. An aluminum metal foam is employed to enhance the PCM thermal behaviors. The geometry is a vertical shell-and-tube LHTESS made with two concentric aluminum tubes. The internal surface of the hollow cylinder is assumed at a constant temperature above the melting temperature of the PCM to simulate the heat transfer from a hot fluid. The external surface is assumed adiabatic. The phase change of the PCM is modelled with the enthalpy porosity theory while the metal foam is considered as a porous media in Darcy-Forchheimer assumption and the Boussinesq approximation is employed. Local thermal non-equilibrium (LTNE) model is assumed. The results are compared in terms of melting time and temperature fields as a function of time for the charging and discharging phases for different porosities and an assigned pore per inch. Results show that the metal foam improves significantly the heat transfer in the LHTESS giving a faster phase change process with respect to pure PCM, reducing the melting time more than one order of magnitude.

1. Introduction
A big issue in the environment problems is the storage of the thermal energy when it is not required. Hence, in order to store the excess energy, the optimization of a thermal energy storage system (TESS) is necessary to overcome this problem. A thermal energy storage system is a storage device [1] useful to accumulate the thermal energy during the excess of energy and release it when required. There are many types of TESS but the most interesting storage system is a Latent Heat Thermal Energy Storage System (LHTESS). This system is based on the Phase Change Materials (PCMs) that have the peculiarity to change their phase from solid to liquid and vice-versa during the heat transfer maintaining the working temperature nearly constant. The PCM used in this study is the paraffin wax, because it is not corrosive, it is chemically stable, the phase change is reversible and the latent heat is very high [2]. Nevertheless these characteristics are not satisfactory for a TESS because the paraffin wax has a low value of thermal conductivity, making the melting time and the solidification time very long respect to a working cycle of charge and discharge of the system. It is necessary to develop a solution in order to overcome this drawback. In the literature there are many solutions like the addition of highly-conductive nanoparticles [3], the usage of metal foam [4] or finned tubes [5]. Particularly, the open-cell metal foam represents the best solutions to make the LHTESS useful for thermal applications 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. Li and Wu [6] numerically studied a 3D model of a shell and tube with PCM for different configuration, Heat Transfer Fluid (HTF) velocity and PCM materials, using the fins to improve the heat transfer. The phase change of the PCM is modelled with the enthalpy porosity method both for charge and discharge phase. The results showed that the extended fins improve the heat transfer by at least 14% respect to the configuration without the fins. The improvement of the PCM with the expanded graphite even reduces the rate of melting by 20%. Atal et al. [7] both experimentally and numerically investigated on a shell-tube arrangement LHTESS with PCM and metal foams. Two different porosities are studied, 95% and 77% and they found that the foam with lower porosity reduces the melting time respect to the higher-porosity foam but in general the metal foam improves the heat transfer respect to the pure PCM. Moreover there is a good agreement between the experimental results and numerical results. A LHTESS for high temperature concentrated solar power plants is numerically studied in [8]. The configuration is a shell-and-tube configuration with a vertical cylindrical tank filled with PCM and various tubes in which the HTF flows from the top to the bottom. The aim of the study is to understand the beneficial effects of the natural convection inside the PCM respect to the pure conductive case. The results show that the melting time is smaller by three hours with respect to the pure conductive case. A similar study to understand the difference between the horizontal configuration and vertical configuration about the effect of the natural convection during the phase change of PCM is made in [9]. Tao and He [10] studied three types of enhancement for a shell-tube configuration and they compare the results. The base case is to fill the system with a pure PCM, the first enhancement is to install fins inside the system, the second and the third are to put a mixed PCM made by different mixture of salts together with fins. The results showed that the only installation of fins reduces the melting time by 36.6% while the second and third enhancement (fins plus mixed PCMs) showed a further reduction of the melting time, respectively by 60.3% and the third 47.7%. Xiao et al [11] 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. Zhou et al [12] investigated experimentally the heat transfer in a PCM/metal foam for a device storage system both for charging and discharging process. They found that the metal foam improved the rate of charge and discharge of the system respect to the pure PCM. A two-dimensional LHTESS based on PCM paraffin RT58 with a copper foam is numerically studied using the LTNE model [13]. A similar experimental study was accomplished in [4] where copper foam with the paraffin wax RT58 are employed for storage application.

In this paper a numerical model of the PCM embedded in metal foam is studied. Local thermal non equilibrium model is assumed and the geometry of TESS is a shell and tube configuration with two concentric aluminum tubes. The enthalpy porosity method is employed and the Darcy-Forchheimer law is used for the modelling of the metal foam. The results are shown in term of melting time, temperature and energy storage for charge and discharge phase.

2. Physical model
LHTESS consists in two concentric shell tubes where the PCM with metal foam is enclosed. The inner and outer tube radiuses are respectively 2 mm and 12 mm, as showed in Fig. 1a. The system has a length of 100 mm along the z-direction.

A 2D domain is considered with the axial symmetry along the z-axis as shown in Fig. 1b. A constant temperature (350 K) is assigned to the inner surface to simulate the HTF while the other surfaces are imposed adiabatic. The gravitation acceleration is along the z-axis. The enthalpy-porosity method is employed to model the phase change of the PCM [14]. This model is useful for those materials that melt in a range of temperature, in fact this method defines a region where the solid and the liquid phase are mixed and there is not a clear solid-liquid interface. This region are called mushy region and it is described by a new parameter called “liquid fraction”. The liquid fraction, indicated with Greek letter $\beta$, represents...
the amount of the liquid phase in a cell of mushy region. It varies from zero to one in the mushy region:

\[
\beta = \begin{cases} 
0 & \text{for } T < T_{\text{solidus}} \\
\frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} & \text{for } T_{\text{solidus}} < T < T_{\text{liquidus}} \\
1 & \text{for } T > T_{\text{liquidus}} 
\end{cases} 
\]  

(1)

\( T \) is the local temperature of the cell, \( T_{\text{liquidus}} \) is the temperature above which the domain is completely liquid and \( T_{\text{solidus}} \) is the temperature below which it is completely solid. The solid part of the mushy region is modelled by adding a source term in the momentum equation. The metal foam is modelled with the Darcy-Forchheimer assumption, because it behaves as a porous media. To evaluate the heat transfer between the foam and the PCM the Local Thermal Non-Equilibrium (LTNE) model is used. In this model the PCM and the metal foam are not in thermal equilibrium and two temperature functions are present, one for the PCM and the other for the metal foam, therefore two energy equations are necessary to describe the field of the temperature [15]. The buoyancy forces are modelled with the Boussinesq approximation.

The hypotheses in the present work are the following:
1) The computational domain is two-dimensional.
2) The metal foam is isotropic and homogenous.
3) The variation of density in the liquid PCM follows the Boussinesq law.
4) The other properties of PCM are constant.

The governing equations are [15]:

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (ru)}{\partial r} + \frac{\partial (w)}{\partial z} = 0
\]  

(2)

\[
\rho_{\text{PCM}} \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial r} + \mu_{\text{PCM}} \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right) + \frac{\partial^2 u}{\partial z^2} \right] + S_r
\]  

(3)

\[
\rho_{\text{PCM}} \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu_{\text{PCM}} \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial w}{\partial r} \right) + \frac{\partial^2 w}{\partial z^2} \right] + S_z
\]  

(4)

Where \( u \) and \( w \) are the velocity of the PCM in liquid phase along respectively \( r \) and \( z \) direction. \( \rho_{\text{PCM}} \) and \( \mu_{\text{PCM}} \) are the density and viscosity of the PCM. \( p \) is the pressure. \( S_r \) and \( S_z \) are the source
terms that taken into account the enthalpy porosity method, the Darcy-Forchheimer and the Boussinesq approximation:

\[
S_v = \frac{(1 - \beta)^3}{(\beta + 0.001)^2} A_{mush} u + \frac{\mu_{PCM}}{K} u + \frac{C_f}{\sqrt{K}} \rho u^2
\]  

(5)

\[
S_v = \frac{(1 - \beta)^3}{(\beta + 0.001)^2} A_{mush} w + \frac{\mu_{PCM}}{K} w + \frac{C_f}{\sqrt{K}} \rho w^2 + \rho_{PCM} g \gamma (T_{PCM} - T_0)
\]  

(6)

The first term in equations (5) and (6) models the solid part in the mushy region. In fact when the liquid fraction \(\beta\) is near to zero, this term increase the resistance to flow of the PCM inside the mushy region. The small number (0.001) is used to avoid division by zero; \(A_{mush}\) is the mushy zone constant which takes into account the damping of the velocity during the solidification [16]. 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 second and third terms are the Darcy-Forchheimer law, where \(K\) is the permeability of the porous media and \(C_f\) is inertial drag factor. The last term in equation (6) is the Boussinesq approximation. In local thermal non-equilibrium model the equation of energy for PCM is [15]:

\[
\rho_{PCM} c_{PCM} \frac{\partial T_{PCM}}{\partial t} + \rho_{PCM} c_{PCM} \left( u \frac{\partial T_{PCM}}{\partial r} + w \frac{\partial T_{PCM}}{\partial z} \right) =
\]

\[
= k_{eff,PCM} \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T_{PCM}}{\partial r} \right) + \frac{\partial^2 T_{PCM}}{\partial z^2} \right) + \alpha_f \gamma h_f (T_{PCM} - T) - \alpha_{PCM} H_L \frac{\partial \beta}{\partial t}
\]  

(7)

while for the metal foam is [16]:

\[
(1 - \varepsilon) \rho_{foam} c_{foam} \frac{\partial T_{foam}}{\partial t} = k_{eff,foam} \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T_{foam}}{\partial r} \right) + \frac{\partial^2 T_{foam}}{\partial z^2} \right) + \alpha_f \gamma h_f (T_{foam} - T_{foam})
\]  

(8)

Where \(k_{eff,PCM}\) and \(k_{eff,foam}\) are, respectively, the effective thermal conductivity of the PCM and metal foam and \(\varepsilon\) is the metal foam porosity. It is hard to predict the effective thermal conductivity in the LTNE model; nevertheless using the relations in [15] it is possible to evaluate the thermal conductivity:

\[
k_{eff} = \frac{\sqrt{2}}{2(M_A + M_B + M_C + M_D)}
\]  

(9)

\[
M_A = \frac{4\sigma}{(2\varepsilon^2 + \pi\sigma(1 - \varepsilon)) k_{foam} + (4 - 2\varepsilon^2 - \pi\sigma(1 - \varepsilon)) k_{PCM}}
\]  

(10)

\[
M_B = \frac{(e - 2\sigma)^2}{(e - 2\sigma) e^2 k_{foam} + (2e - 4\sigma - (e - 2\sigma)e^2) k_{PCM}}
\]  

(11)
\[
M_C = \frac{\left( \sqrt{2} - 2e \right)^2}{2 \pi \sigma^2 \left( 1 - 2e \sqrt{2} \right) k_{f,\text{foam}} + 2 \left( \sqrt{2} - 2e - \pi \sigma^2 \left( 1 - 2e \sqrt{2} \right) \right) k_{\text{PCM}}} \quad (12)
\]

\[
M_D = \frac{2e}{e^2 k_{f,\text{foam}} + 4 - e^2 k_{\text{PCM}}} \quad (13)
\]

\[
\sigma = \left( \frac{\sqrt{2} \left( 2 - \left( \frac{5}{8} e^3 \sqrt{2} \right) - 2e \right)}{\pi \left( 3 - 4e \sqrt{2} - e \right)} \right)^{1/2} \quad (14)
\]

\[e = 0.339 \quad (15)\]

then the effective thermal conductivity of the PCM and metal foam are:

\[
k_{\text{eff,PCM}} = k_{\text{eff}} \bigg|_{f,\text{foam}=0} \quad (16)
\]

\[
k_{\text{eff,foam}} = k_{\text{eff}} \bigg|_{\text{pcm}=0} \quad (17)
\]

In the equations 7 and 8 the heat exchange between PCM and metal foam occurs by means of the product \(\alpha_f h_{sf}\). \(h_{sf}\) is the local heat transfer coefficient, \(\alpha_f\) is the surface area density of the metal foam. The surface area density represents the total heat exchange area between PCM and metal foam. The relations of Calmidi and Mahajan are employed to evaluate \(\alpha_f\) and \(h_{sf}\) [17]:

\[
\alpha_f = \frac{3\pi d_f}{\left( 0.59 d_p \right)^2 \left( 1 - e \frac{1^{1-e}}{0.064} \right)} \quad (18)
\]

\[
h_{sf} = \begin{cases} 
(0.76 Re_d^{0.4} Pr_{pcm}^{0.37}) \left( \frac{k_f}{d_f} \right), & 1 \leq Re_d \leq 40 \\
(0.52 Re_d^{0.5} Pr_{pcm}^{0.37}) \left( \frac{k_f}{d_f} \right), & 40 \leq Re_d \leq 1000 \\
(0.26 Re_d^{0.6} Pr_{pcm}^{0.37}) \left( \frac{k_f}{d_f} \right), & 1000 \leq Re_d \leq 2 \times 10^5 
\end{cases} \quad (19)
\]

where \(Re_d\) is the local Reynolds number related to ligament diameter:

\[
Re_d = \frac{\rho V d_f}{\mu} \quad (20)
\]

\(d_f\) 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 [17]:

...
\[
\frac{d_f}{d_p} = 1.18 \left( \frac{1 - \varepsilon}{3\pi} \right)^{1/2} \left( \frac{1}{1 - e^{(1 - \varepsilon)/0.08}} \right) 
\]

(21)

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

(22)

where \(\omega\) 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 20 Pore Per Inch (PPI).

The Darcy-Forchheimer law is the following:

\[
\frac{\Delta p}{L} = \frac{\mu}{\rho} \bar{V} + \rho C_F \bar{V}^2 
\]

(23)

where \(\Delta p\) is the pressure drop and \(L\) is the length of the porous media across which the pressure drop appeared. It describes the behavior of the metal foam. The permeability and drag factor or inertia coefficient values are evaluate by the following, [17]:

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

(24)

\[
C_F = 0.00212(1 - \varepsilon)^{-0.132} \left( \frac{d_f}{d_p} \right)^{-1.63} 
\]

(25)

The paraffin wax is the paraffin RT58 of the Rubitherm [18] and the properties are listed in Table 1.

| Physical properties                  | Paraffin RT58 [18] |
|--------------------------------------|--------------------|
| Density [kg/m³]                     | 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                |

In the Boussinesq approximation the operating temperature is equals to 321 K.

3. Numerical model

The finite volume method [19] is used for resolving the governing equation (2), (3), (4), (7) and (8) using the commercial code Ansys Fluent 15.0 [20]. For the inner boundary condition, at \(r = 2\) mm \(T_{PCM}\) and \(T_{foam}\) are equal to 350K. The SIMPLE algorithm is employed for coupling the pressure and the velocity; the green-gauss cell gradient evaluation is used for the spatial discretization; the second order upwind scheme is used for momentum and energy equation. The convergence is imposed by set the residual to \(10^{-5}\) for continuity and moment equations while \(10^{-8}\) for energy equation. A transient
mode is enabled and a temporal independence test is made and the time step size equal to 0.2 s was the best choice for the numerical accuracy. The LTNE has been implemented using a user-defined function for the calculation of the local heat transfer coefficient indicated in equation (19), while the energy equations are automatically solved with a module of FLUENT that overlaps the fluid and solid zone.

![Figure 2 Independent test for the mesh.](image)

The grid independent study is made with five different meshes: 4 x 10, 8 x 20, 12 x 30, 20 x 50 and 40 x 100 nodes and the mesh with 20 x 50 nodes is chosen. In literature there are few experiments about PCM melting in cylinders.

![Figure 3 Clean case: a) average liquid fraction b) average temperature c) average specific energy](image)
Nevertheless, the accuracy of the enthalpy-porosity method used in this model is tested using the work of Krishnan et al. [21], where a 2D non-dimensional enclosure is studied. In [21] a two temperature model is implemented with LTNE assumption and various parameters are studied to understand the influence on the PCM melting. Therefore, a comparison between the work [21] and the enthalpy-porosity method of this model is carried out, using the same boundary conditions and properties. The results showed a good agreement. In particular, in different instants of time the evolution of the PCM temperature at the mid-height of the domain is evaluated and the differences between this model and [21] are imperceptible.

4. Results and discussion
The results are expressed for charging and discharging process at different values of porosity, 80% and 90% with an assigned PPI equals to 20. In all cases the LTNE model is employed and for the charging process the temperature of the internal cylinder is assumed to 350 K and for discharging process is 300K. The other surfaces are assumed adiabatic. A comparison in terms of temperature, liquid fraction and specific energy stored is accomplished. Fig. 3 depicted the average liquid fraction (a), average temperature (b) and average energy stored (c) as functions of time for a LHTESS with pure paraffin wax both for charging and discharging process. The rate of melting is very low because of the low value of the thermal conductivity; in fact the charging process is completed at nearly 4500 seconds and the discharging process lasts 4000 seconds. Therefore the discharging process is faster than the charging process in the clean case. Fig. 4 showed a comparison between the pure paraffin wax (CLEAN case) with paraffin inside the metal foam in terms of liquid fraction, temperature and average energy stored.

Figure 4 Comparison between the pure PCM and PCM with metal foam in term of average liquid fraction (a), average temperature (b) and energy stored (c) for charging and discharging phase.
It is clear that the presence of the metal foam improves significantly the melting rate during the charge phase and the solidification rate during the discharge phase; in fact the scale of the time is logarithmic. Even with the metal foam the discharging process is faster. A further comparison between two metal foams at different porosity value is made in fig. 5. the metal foam considered have a porosity equal to 80% and 90%, respectively. The order of magnitude of the rate change phase for charging and discharging process for both porosities is similar but the metal foam with 80% of porosity is faster. Therefore small values of porosity increase the rate of the phenomenon, but the energy stored is lower, as showed in fig. 5c.

5. Conclusions
A numerical investigation on the latent heat thermal energy stored system was accomplished. Both charging and discharging process were performed. The materials employed are the paraffin wax as PCM and the metal aluminum foam. The enthalpy-porosity theory was employed to simulate the phase change process. The metal foam was modelled with the Darcy-Forchheimer law for the fluid flow and the LTNE model for the energy. The results found that the presence of the metal foam improves significantly the thermal performance of the LHTESS; in fact the rate of melting during the charge phase and the rate of solidification during the discharge phase are faster more than one order of magnitude respect to the pure PCM. Moreover, the reduction of the porosity determines an increase of the heat storage and heat release rate.

![Figure 5](image_url)

**Figure 5** comparison between the two metal foam with different porosity in term of average liquid fraction (a), average temperature (b) and energy stored (c) for charging and discharging phase.
6. References

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