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NUMERICAL SIMULATION OF THERMAL ENERGY STORAGE WITH PHASE CHANGE MATERIAL 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 used is a pure paraffin wax with melting over a range of temperature and a high latent heat of fusion. However, its thermal conductivity is very low (about 0.2 W/K m) and a method to enhance the heat transfer is putting the PCM into aluminum metal foam. The geometry of the system under investigation is a vertical shell and tube LHTES 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 other external surfaces are assumed adiabatic or with heat losses toward the external ambient at assigned temperature. Two models are compared in reference to the heat transfer between the metal foam and the PCM, the Local Thermal equilibrium (LTE) and the Local Thermal non Equilibrium (LTNE). Results as a function of time for the charging phase are carried out for different porosities and assigned pore per inch (PPI). The results show the presence of metal foam improves significantly the heat transfer in the LHTES.

INTRODUCTION
Nowadays the energy consumption is always increasing, even if the energy sources could satisfy the energy demand, this is not sufficient because it is indispensable to balance the intermittent demand of energy with the continuous energy supply. Therefore, the optimization of thermal energy storage is necessary in order to overcome this problem. The researches have been focused on the Latent Heat Thermal Energy Storage System (LHTESS). A Latent Heat Thermal Energy Storage System (LHTESS) is thermal buffer device that permits to store thermal energy when it is abundant and release them when required [1]. It is based on materials that during the charging process or discharging process maintain their temperature nearly constant because they change phase. These materials are commonly called Phase Change Materials (PCMs). It is important that the PCMs have a high value of Latent Heat. There are many types of PCMs but in this study the paraffin wax is used because it is cheap, chemically stable, reversible and non-toxic [2]. However, the paraffin has a low value of thermal conductivity [2] (about 0.2 W/m K), therefore it is necessary to develop ameliorative solutions. In literature there are many proposals as insertion of ceramics nanoparticle in the PCM [3] using of metal foam [4] or finned tube [5]. The open-cell metal foams represent the best choice to overcome this drawback because they improve the effective thermal conductivity of the entire system thanks to high numbers of pores. In literature there are many works about the thermal behavior between the metal foam and the PCM; Siahpush et al [6] compared an experimental test with a numerical model in order to study the thermal behavior of a cylindrical system with PCM and copper foam. Krishnan et al. [7] accomplished a numerical study on the PCM with metal foam inside a rectangular domain using the LTNE model. An horizontal shell-tube LHTESS integrated with radial fins is experimentally studied in [8] for charge and discharge phase with different Reynolds number of the HTF and different numbers of fins. The results present that the HTF velocity has a great influence of the PCM melting rate in fact the melting time was reduced by 58% for Reynolds number equal to 2000 respect to 1000. Moreover, if the numbers of fins are doubled from 24 to 48, the melting time was reduced by 76%. A shell-and-tube device system for thermal energy storage is investigated in [9] with a paraffin as PCM and graphite foam. The results showed that the graphite foam improves the melting rate and the HTF velocity has a great influence on the phase change process of the PCM. Moreover, a comparison with an experimental device is made and the results present a good agreement between the numerical simulations. Du et al. [10] experimentally investigated a compound enhancement made by graphite foam and finned tube in order to improve a LHTESS based on paraffin wax as PCM. Three samples are built, one with only PCM, the second with graphite foam and

the last with graphite foam and finned tube. The experiments are made for different operating conditions. They found that the melting time is reduced respect to the pure PCM but the finned tube could lead an increment of the pressure because its presence could create a large temperature gradient between the bottom and the top of the device leading to an expansion of the PCM volume only on the bottom of the device. An entropy optimization for a LHTESS based on PCM is made in [11] using the entropy generation number [12]. The effect of HTF mass flow rate, inlet flow temperature and PCM material are analyzed and the conclusions states that the minimum entropy generation number is provided by the minimum inlet temperature and the higher initial temperature of the PCM during the solidification process. Atal et al. [13] experimentally and numerically studied a thermal energy storage device in cylindrical domain using paraffin and metal foam for different porosity. They found that there is a good agreement between the experimental data and the numerical results. In this paper a numerical investigation on Latent Heat Thermal Energy Storage System (LHTESS) based on a phase change material (PCM) is accomplished. The PCM used is a pure paraffin wax. Aluminum foam is employed to improve the heat transfer inside the system. The geometry of the system under investigation is a vertical shell-tube LHTES made with two concentric aluminum tubes. The phase change of the PCM is modelled with the enthalpy porosity theory while the metal foam is considered as a porous media that obeys to the Darcy-Forchheimer law. Two energy model are used, the Local Thermal equilibrium (LTE) and Local Thermal Non Equilibrium (LTNE).The results show that at high porosity the LTE and LTNE models tend to have the nearly the melting time while at low porosity the LTNE has a larger melting time. Moreover, the presence of metal foam improves significantly the heat transfer in the, reducing the melting time more than one order of magnitude.

NOMENCLATURE

A_{mush}	=	Mushy zone constant [kg m^{-3} s^{-1}]
b	=	Second Letter in English Alphabet
c	=	Specific Heat [J kg^{-1} K^{-1}]
C_f	=	Inertial drag factor
d	=	Diameter [m]
g	=	gravity acceleration [m s^{-2}]
h_{sf}	=	interstitial h. transf. coeff. [W m^{-2} K^{-1}]
H_L	=	Latent Heat of PCM [J kg^{-1}]
k	=	Thermal conductivity [W m^{-1} K^{-1}]
K	=	Permeability of porous media [m^2]
p	=	Pressure [Pa]
Pr	=	Prandtl Number
Re	=	Reynolds number
S	=	Source term
t	=	Time [s]
T	=	Temperature [K]
V	=	Local Velocity of liquid PCM [m/s]

Greek Symbols

α_{sf}	=	Surface area density [m^{-1}]
β	=	Liquid Fraction
γ	=	therm. Expansion factor [K^{-1}]
ε	=	Porosity
ρ	=	Density [kg/m^3]
μ	=	Dynamic Viscosity [Pa s]
ω	=	Pore density [Pore per Inch (PPI)]

Subscripts

0	=	Operating
eff	=	Effective
f	=	Fiber
Liquidus	=	Liquidus
m	=	Metal foam
p	=	Pore
PCM	=	Phase change material
Solidus	=	Solidus

Mathematical Models

The 2D numerical model is a concentric shell-and-tube with the inner radius and outer radius equal respectively 2 mm and 12 mm. The Length of the tube is 100 mm and the gravitational acceleration is along the length of the tube. The heat transfer fluid flows in the inner channel and it transfers the heat to the PCM enclosed between the outer shell tube and inner tube as shown in fig.1.

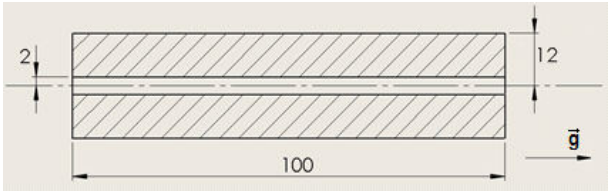
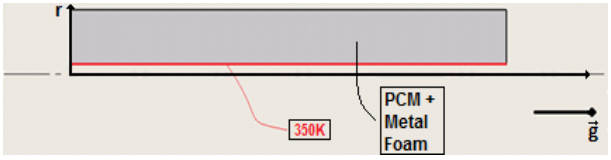
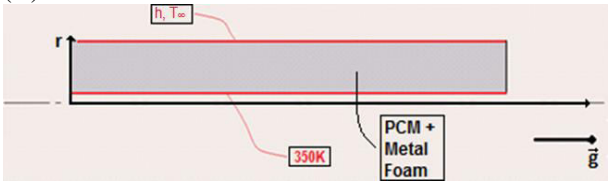


Figure 1 PHYSICAL MODEL OF THE LHTESS.

The axial symmetry is assumed. Two configurations are considered, configuration A and configuration B. In the configuration A (fig.2A) the inner surface is assumed at constant temperature with a value of 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 on the outer surface a convective heat transfer is considered to simulate the heat losses toward the ambient.



(A)



(B)

Figure 2: THE TWO CONFIGURATIONS WITH DIFFERENT BOUNDARY CONDITIONS FOR THE OUTER SURFACE: (A) ADIABATIC AND (B) CONVECTIVE HEAT TRANSFER.

The simulation of melting PCM is modelled with enthalpy-porosity method [14]. In this method a mixed solid-liquid region is defined where the solid phase and liquid phase are not clearly separable. This zone is modelled as a "pseudo" porous zone where a new parameter, called "liquid fraction", represents the ratio between the liquid phase part of a representative volume and the total volume. Therefore, the solid-liquid region is defined in a range of temperature between $T_{solidus}$ and $T_{liquidus}$. The value of the liquid fraction, β, is then:

$$\begin{cases} \beta = 0 & \text{for} \quad T < T_{solidus} \\ \beta = \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & \text{for} \quad T_{solidus} < T < T_{liquidus} \\ \beta = 1 & \text{for} \quad T > T_{liquidus} \end{cases} \tag{1}$$

Where T is the local temperature. The metal foam is modelled like a porous medium using the Darcy-Forchheimer equation. For the energy interaction between the PCM and the metal foam, the models Local Thermal Equilibrium and Local Thermal non-Equilibrium are used. In the LTE the metal foam and the PCM are in thermal equilibrium while in the LTNE two Temperatures are defined, one for the metal foam and one for the PCM; therefore, two energy equations are necessary. The governing equations are:

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

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

In LTE model the energy equation is:

$$\overline{\rho c}\frac{DT}{Dt} = k_{eff}\nabla^2 T - \varepsilon \rho_{pcm} H_L \frac{\partial \beta}{\partial t} \tag{4}$$

While in LTNE model the energy equation for the PCM:

$$\begin{aligned} &\varepsilon \rho_{pcm} c_{pcm} \frac{DT_{pcm}}{Dt} = k_{pcm,eff}\nabla^2 T_{pcm} + \\ &+ \quad h_{sf}\alpha_{sf}\left(T_{pcm} - T_m\right) - \varepsilon \rho_{pcm} H_L \frac{\partial \beta}{\partial t} \end{aligned} \tag{5}$$

and for the metal foam:

$$(1-\varepsilon)\rho_m c_m \frac{DT_m}{Dt} = k_{m,eff}\nabla^2 T_m + h_{sf}\alpha_{sf}\left(T_m - T_{pcm}\right) \tag{6}$$

where 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 product ρc is [15]:

$$\overline{\rho c} = (1-\varepsilon)\rho_m c_m + \grave{o}\rho_{pcm} c_{pcm} \tag{7}$$

where ρ_m and c_m are respectively the density and specific heat of the metal foam, ε is the porosity of the metal foam and c_{pcm} is the specific heat of PCM. k_{eff} is the effective thermal conductivity [15]:

$$k_{eff} = (1-\varepsilon)k_m + \varepsilon k_{pcm} \tag{8}$$

k_m e k_{pcm} are respectively the thermal conductivities of metal foam and PCM. The calculation of the thermal conductivity $k_{pcm,eff}$ and $k_{m,eff}$ are reported in Boomsma et al. [19] and it is not reported here for brevity. H_L is the latent heat of the PCM and t is the time. The vector $\vec{S}$ represents a global source term given by the following equation:

$$\begin{aligned} \vec{S} &= \frac{(1-\beta)^2}{\left(\beta^3 + 0.001\right)^3} A_{mush}\vec{V} + \\ &+ \quad \frac{\mu}{K}\vec{V} + \frac{C_F}{\sqrt{K}}\rho\vec{V}\left|\vec{V}\right| + \rho\vec{g}\gamma\left(T - T_0\right) \end{aligned} \tag{9}$$

The first term on the right side models the presence of the solid part in the mixed region called Carman-Koseny term and the number 0.001 is necessary to avoid division by zero [16], A_{mush} is the mushy zone constant that acts as a damping factor of the velocity during the solidification [17]. Its value is set to 10^5 kg/m^{3}s. 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 calculated with the following [18]:

$$K = 0.00073(1-\varepsilon)^{-0.224}\left(\frac{d_f}{d_p}\right)^{-1.11} d_p^2 \tag{10}$$

$$C_F = 0.00212(1-\varepsilon)^{-0.132}\left(\frac{d_f}{d_p}\right)^{-1.63} \tag{11}$$

The last term is the Boussinesq approximation, used to simulate the natural convection in the PCM. The vector g is the gravitational acceleration, T_0 is the operating temperature and γ is the thermal expansion coefficient.
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 [18]:

$$\frac{d_f}{d_p} = 1.18\sqrt{\frac{1-\varepsilon}{3\pi}}\left(\frac{1}{1-e^{1(1-\varepsilon)/0.04}}\right) \quad (12)$$

$$d_p = \frac{0.0224}{\omega} \quad (13)$$

ω is pore density that represents the number of pores across one linear inch. The subscripts "m" and "pcm" refer respectively to the properties of the metal foam and the properties of the PCM. h_{sf} is the interstitial local heat transfer coefficient; α_{sf} is the surface area density of the metal foam that represents the whole contact between PCM and metal foam. Their expressions are:

$$h_{sf} = aRe_f^b Pr_{pcm}^{0.37}\left(\frac{k_f}{d_f}\right) \quad (14)$$

$$\alpha_{sf} = \frac{3\pi d_f}{\left(0.59 d_p\right)^2}(1-e^{\frac{1(1-\varepsilon)}{0.04}}) \quad (15)$$

With $a = 0.76$ and $b = 0.4$ for $1 \le Re_f < 40$; $a = 0.52$ and $b = 0.5$ for $40 \le Re_f < 1000$, $a = 0.26$ and $b = 0.6$ for $1000 \le Re_f < 2*10^5$. The Reynolds number is referred to the fiber diameter, in fact:

$$Re_f = \frac{\rho V d_f}{\mu} \quad (16)$$

The PCM paraffin is RT58 and the metal foam is aluminum. In the table 1 are listed the properties of the materials [20]. The thermophysical quantity values are considered constant during the melting for both phases.

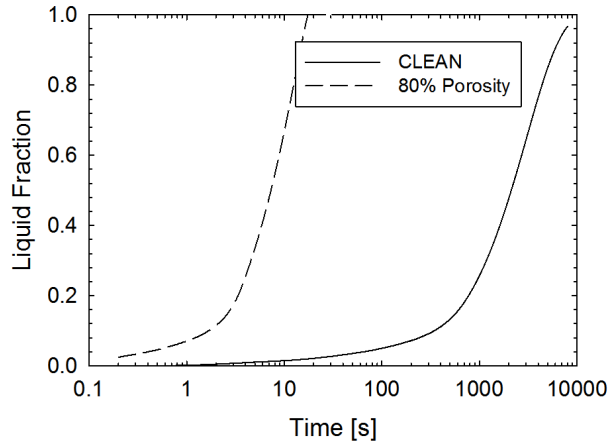
TABLE 1: PROPERTIES OF THE PARAFFIN WAX

Paraffin RT58	Values
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

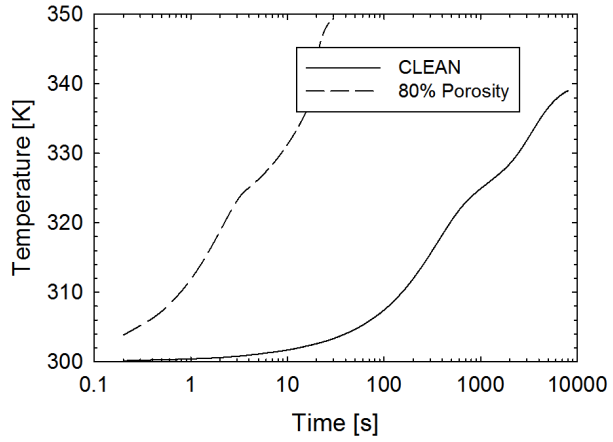
Results and discussion

The results are expressed in term of average liquid fraction, temperature and energy for different value of porosity with a constant value of PPI equals to 20. Both models of LTE and LTNE are used. The internal surface of the cylinder is assumed equals to 350 K. The external surface is assumed adiabatic or with heat losses to 5 W/m^{2}K toward a room temperature of 300 K.

In fig 3 it is reported a comparison between the pure PCM and the PCM with metal foam at 80% of porosity for adiabatic configuration. It is clear that the presence of the metal foam significantly improve the thermal behavior of the system.



(A)



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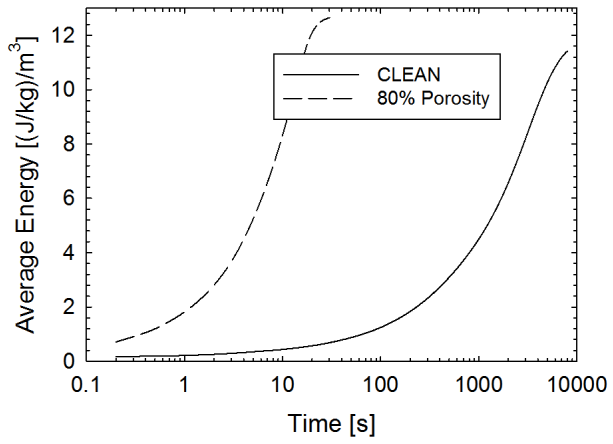
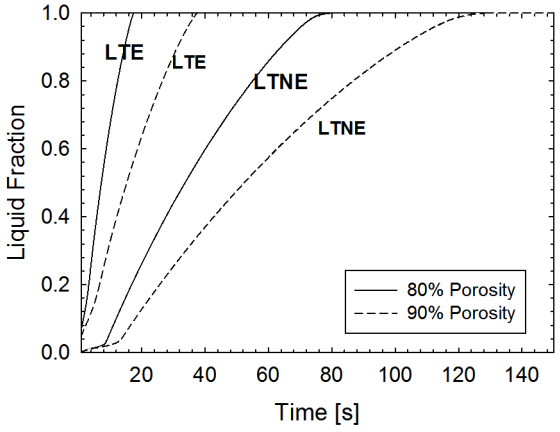


(C)

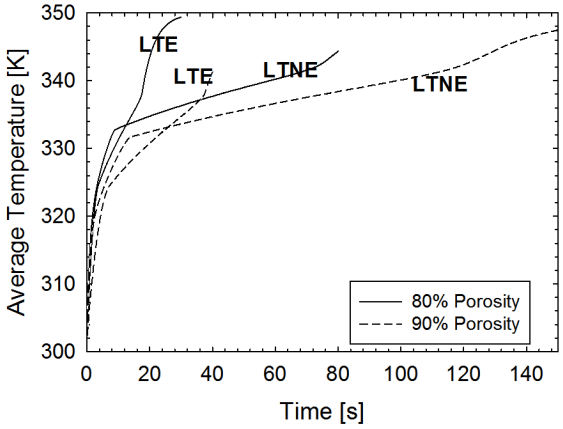
Figure 3: COMPARISON BETWEEN PURE PCM AND PCM WITH METAL FOAM

In fact the evolution of the average liquid fraction in figure 3.a shows that the velocity of melting with metal

foam is faster than the pure PCM of more one order of magnitude. The average temperature of the system follows the same path of the average liquid fraction but there is a change of the evolution because of the beginning of the melting in major part of the domain.
Another important aspect is the effect of the porosity on the thermal behavior of the system. Figure 4 shows a comparison between two metal foams with different porosity, 80% and 90% with LTE model and LTNE model.



(A)



(B)

Figure 4: COMPARISON BETWEEN TWO DIFFERENT METAL FOAM BOTH FOR LTE AND LTNE MODEL.

It is clear that in the LTNE model the PCM employs more time for melting because there are a difference of temperature between the metal foam and the PCM. Nevertheless, higher porosity reduces the difference between the LTE and LTNE because the area surface density tends to increase for higher porosity. It is more clear for porosity of 95% or 99% (this last porosity is only a numerical extrapolation, it is does not exist physically). The table 2 shows the melting time for different porosity and for both model using the configuration A.

It is noted that the percentage variation between the LTE and LTNE is minor for porosity of 99%.

TABLE 2: COMPARISON BETWEEN LTE AND LTNE FOR CONFIGURATION A

Porosity [%]	Melting time [s]		Difference LTNE-LTE [s]	Percentage variation
	LTE	LTNE		
90	37.4	119.8	82.4	220%
95	76.6	195.4	118.8	155%
99	366.2	670.6	304.4	83%

Finally a comparison between the both configurations is made in term of melting time. Table 3 shows the melting time for configuration A and B for LTE model.

TABLE 3: COMPARISON BETWEEN CONFIGURATION A AND CONFIGURATION B.

Porosity [%]	Melting time (Config. A)	Melting time (Config. B)	Variation
80	17.6	17.6	0
90	37.4	37.6	0.2
95	76.6	77.4	0.8
99	366.2	386.8	20.6

It seem that for lower porosity the melting time is the same for both configurations while for higher porosity the difference is more pronounced.

CONCLUSION

In this work a numerical investigation of a LHTESS with PCM and aluminum foam is accomplished. It is clear that the presence of the metal foam improves the heat transfer inside the system reducing the time of melting. Moreover, higher porosity increases the melting time because the effective thermal conductivity is lower in relation to equation 8. The comparison between the LTE and LTNE is accomplished and for higher porosity the two models tend to close each other in term of melting time. Moreover the two configurations return the same melting time for lower porosity.

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