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Entropy generation analysis of parallel plate channels for latent heat thermal energy storages

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ABSTRACT

In TES system the thermal energy is stored by changing the temperature of a storage medium and/or adopting the Phase Change Material (PCM). One of the main goal for a TES system is to optimize the charging and discharging rate of thermal energy improving the heat transfer between the working fluid and the TES system by increasing the surface exchange area. In the present work a computational investigation on thermal energy storage system using Phase Change Material (PCM) is accomplished. The system is built by a set of parallel plate channels, half of them are filled with PCM and in the others the working fluid is free to flow. Different channels per unit of length (CPL) are investigated. Two approaches are evaluated: a heat transfer conjugate approach where every geometrical detail is evaluated and a porous media approach where the TES system is considerate homogeneous. A comparison between a conjugate-heat-transfer direct model and a porous medium model is carried out. The porous medium is modeled using the Local Thermal Equilibrium assumption for the heat transfer and for dynamic behavior the Darcy law is employed. An entropy generation analysis is carried out for the porous medium model and the results are showed in term of temperature evolution, liquid fraction and entropy generation.

1. INTRODUCTION

System for the energy saving and storage are mainly used in many industrial and commercial applications to supply thermal energy when it is required. The energy demand has always been intermittent while the energy supply is often provided in continuous way. In order to match the energy demand with the energy supply, a Thermal Energy Storage (TES) system is necessary to overcome this issue, in particular by means of Latent Heat Thermal Energy Storage (LHTES) systems with PCMs [1]. In LHTES systems, the energy is stored using the Phase Change Materials because they have high values of latent heat [2]. The Phase Change materials have the advantage to store the thermal energy during the phase change process maintaining the operating temperature nearly constant. In literature have been studied different kind of PCM [3] with various physical properties and in different applications [4] such as solar energy, building, electronic cooling.

In thermal storage applications, many authors have investigated the influence of the PCM, for example Kurnia et al. [5] have numerically investigated thermal energy storage for different configurations in charging and discharging time with PCM. By the results the presence of PCM influences the heat transfer performance. A simplified analysis of parallel plate system with parallel channels as a porous media is accomplished in Buonomo et al. [6] for a sensible heat transfer thermal storage system. The analysis has estimated an optimized configuration in term of number of channel per unit of length (CPL) to balance the pressure drop and heat transfer rate in sensible heat transfer thermal storage. Two kind of approaches are evaluated, conjugate-heat-transfer direct approach and porous media approach. The results showed that for low CPL values (<4) the two approaches present some significant differences whereas these differences become very small for higher CPL. In literature there are few works about the interaction between PCM and air in a matrix system useful to increase the surface heat transfer area. Iten et al. [7] have studied the interaction between phase change material with air as heat transfer fluid in thermal energy storage system while Stathopoulos et al. [8] both experimentally and numerically have studied a PCM-air heat exchanger. The exchanger is a set of 16 parallel placed aluminum plates filled with paraffin. The unit was connected with an experimental platform allowing air circulation through the plates. By the results a good agreement between the numerical and experimental data is demonstrated.

The entropy generation analysis [9] is a technique to quantify the significance of the irreversibilities. This analysis uses the second law of thermodynamics for thermal design optimization and it was developed for heat transfer and fluid flow by Bejan in 1996. The entropy generation for latent heat thermal storage systems have been reviewed in Jegadheeswaran et al. [10]. It is important to choose an appropriate PCM because it affects the LHTS systems performance and a list of potential PCMs for different operating temperatures and different applications is carried out in [11]. A calculation of the entropy variation is produced by El-Dessouky and Al-Juwayhel [12].

In the present work a computational investigation on thermal energy storage system using Phase Change Material (PCM) is accomplished. The system is built by a set of parallel plate channels, half of them are filled with PCM and in the others the working fluid is free to flow. Different channels per unit of length (CPL) are investigated. Two approaches are evaluated: a heat transfer conjugate approach where every geometrical detail is evaluated and a porous media approach where the TES system is considerate homogeneous. A comparison between a conjugate-heat-transfer direct model and a porous medium model is carried out. The porous medium is modeled using the Local Thermal Equilibrium assumption for the heat transfer and for dynamic behavior the Darcy law is employed. An entropy generation analysis is carried out for the porous medium model. Numerical simulations are carried out using the Ansys-Fluent code for the conjugate-heat-transfer direct model with $2n$ channels for direct and equivalent porous medium. Results in terms of temperature evolution, melting time, entropy generation and Bejan number as function of time are presented and a comparison between the two models is accomplished.

2. PHYSICAL MODEL

The system under analysis is made up of a set of different parallel plates; in half of them PCM is present and in the others, there is the working fluid, air flow. The depiction of the system is shown in Fig.1.

The height of a single elementary channel is indicated as H and the thickness is equal to $2s$ and the cross section area, where the fluid flows, is $H \times W$. The length L of the parallel plate is 1 m.

The heat transfer working fluid is air while the solid material is a ceramic material, cordierite. The PCM adopted in this analysis is Potassium carbonate (K_2CO_3). The thermal properties of the heat transfer fluid are temperature dependent, while the properties of the solid and the phase change material are assumed temperature independent. The variation of thermal properties for the air is defined by the following equations [13].

$$c_p = 1.06 \cdot 10^3 - 0.449T + 1.14 \cdot 10^{-3} T^2 - 8 \cdot 10^{-7} T^3 + 1.93 \cdot 10^{-10} T^4 \tag{1}$$

$$k = -3.93 \cdot 10^{-3} + 1.02 \cdot 10^{-4} T - 4.86 \cdot 10^{-8} T^2 + 1.52 \cdot 10^{-11} T^3 \tag{2}$$

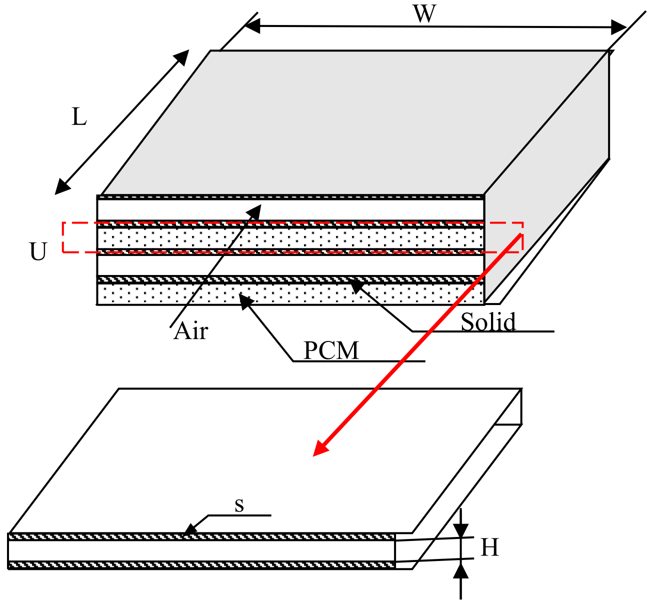


Figure 1. Sketch of the parallel plates with the single channel size

Table 1. Thermophysical properties

Material	Density (kg m^3)	Specific heat (J kg^{-1} K^{-1})	Thermal Conductivity (W m^{-1} K^{-1})	Latent Heat (kJ kg^{-1})	Melting Temperature (K)	Dynamic Viscosity (Pa s)
Cordierite	2300	900	2.5	-	-	-
Air [13]	Ideal gas Law	Eq. (1)	Eq.(2)	-	-	Sutherland Law
K_2CO_3 [4]	2290	1513.69 [14]	2	235.8	1170.15	-

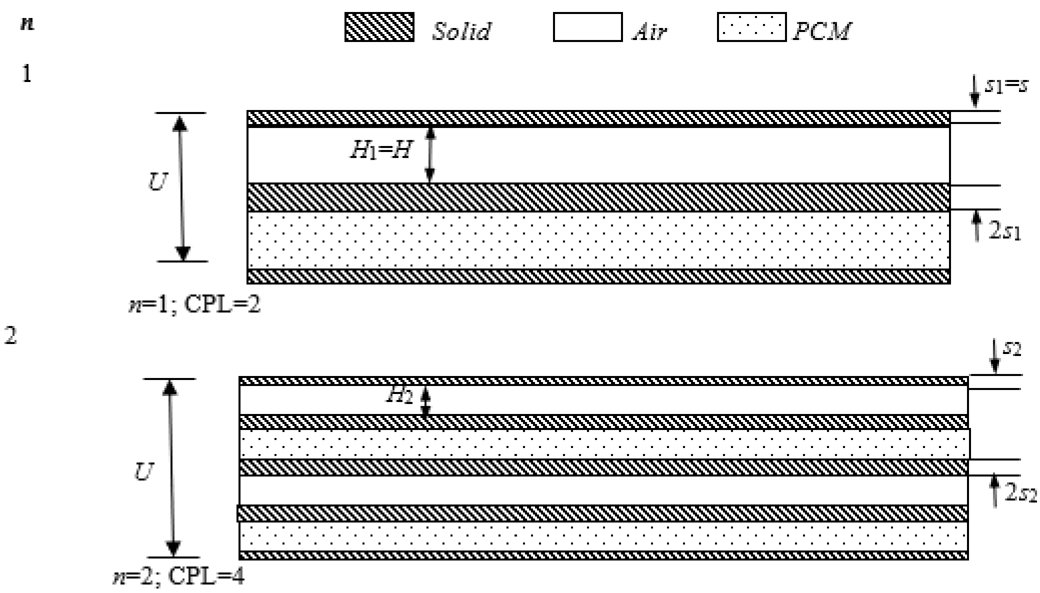


Figure 2. Sketch of honeycomb system with 1, 2 and 3 channel per unit of length (CPL)

The properties of materials are listed in Table 1.

The parallel plates system is crossed by the air while the PCM is confined inside it, therefore the PCM is blocked in the half of closed channels and the others can be crossed, as it showed in Fig. 1. Different parallel plates systems are studied for different air Channel per unit of length (CPL) with the same porosity and volume. In particular, the parallel plates system is studied with CPL equal to 1 and 4 and by the results the permeability, effective thermal conductivity, local heat transfer coefficient and specific area density are studied. The parallel plates system with different CPL is showed in Fig. 2.

The relation between the channel height H and the thickness s for different CPL is:

$$H_n = \frac{H}{2^{n-1}}; \quad s_n = \frac{s}{2^{n-1}} \quad for\ n = 1,2.... \tag{3}$$

where H and s are the values for 1 CPL and n = $\log_2$CPL. Therefore, the porosity for this configuration is:

$$\varepsilon = \frac{V_{air}}{V_{total}} = \frac{H_n}{2H_n + 4s_n} = \frac{H}{2H + 4s} \tag{4}$$

where V_{air} is the air volume and V_{total} is the packaging volume. The fraction of the PCM phase is equal to ε because half of channels are filled with PCM and the fraction of the cordierite is equal 1-2ε. The relationship between unit of length U, channel height H and thickness s is:

$$U = 2H + 4s \rightarrow \begin{cases} H = U\varepsilon \\ s = (1-2\varepsilon)/4 \end{cases} \tag{5}$$

The porosity value ε is equal to 0.4 m and the unit of length U is set to 0.2 m. The direct simulation of the parallel plates systems is compared with a porous model with the same characteristics such as permeability and effective thermal conductivity. The enthalpy-based method is employed to simulate the melting and solidification of PCM [15]. In this method, during the phase change, a mixed solid-liquid phase zone is present, called mushy zone. This region is defined using a parameter called liquid fraction, β. This value ranges from 0 to 1 in the mushy zone, while it is equal to zero when the zone is fully solid and it is 1 when the zone is fully liquid:

$$\begin{cases} \beta = 0 & T < T_m - \Delta T/2 \\ \beta = \dfrac{T - T_m + \Delta T/2}{\Delta T} & T_m - \Delta T/2 < T < T_m + \Delta T/2 \\ \beta = 1 & T > T_m + \Delta T/2 \end{cases} \tag{6}$$

where T is the local temperature, T_m is the PCM melting temperature, ΔT is the temperature range in which the phase change happens. The mushy zone is present in the range temperature ΔT. In this study, the ΔT is imposed to 2K in order to avoid numerical instability. The PCM is enclosed inside the channels and it is considered fixed without any movement, while the air passes through with a mass flux equal to 0.05 kgm^{-2}s^{-1}.

It is more difficult to simulate the parallel plates system when the number of CPL increases, therefore an equivalent porous model is used and a comparison with the direct simulation is carried out. In fact, the parallel plates matrix can be considered as a porous medium where it is necessary to define the characteristics such as effective thermal conductivity k_{eff} and permeability K. The honeycomb porous medium is anisotropic with an effective thermal conductivity that has a value along z direction different respect to x and y directions, while the permeability K is considered only along the z direction because along the x and y directions the permeability is null. The PCM, inside the porous model, is part of the solid phase, because the liquid PCM, after the melting, does not move because it is blocked inside the cavity closed. Furthermore, Pal and Joshi [16] established that the natural convection of the PCM is neglected in a honeycomb structure. The permeability K is not influenced by the PCM, because it depends by the dynamic effects of the porous medium.

K is evaluated by the study of Bahrami et al. [17] where the average velocity uavg in a single parallel plate channel with is:

$$u_{avg} = \frac{H^2}{12\mu_f}\left(\frac{\Delta p}{L}\right) \tag{7}$$

in which Δp is the pressure drop along the channel and μf is the dynamic viscosity of the air. For low values of Reynolds, a porous medium obeys to the Darcy law:

$$\frac{\Delta p}{L} = \frac{\mu_f}{K} u_D \tag{8}$$

where u_D is the Darcy velocity, the relation between Darcy velocity and average velocity is $u_D = \varepsilon u_{avg}$. The permeability K for a single channel is evaluated as:

$$K = \frac{\varepsilon H^2}{12} \tag{9}$$

while the permeability for different CPL is:

$$K = \frac{\varepsilon H_n^2}{12} \tag{10}$$

The honeycomb direct model is a conjugate heat transfer problem and it is compared with a porous model considering the following hypothesis:

- Natural convection is neglected. This is valid for the PCM because the enclosure cell is very small and the phenomenon does not appear. [16]
- The porous model is anisotropic. The thermal properties have different values along the cartesian directions.
- The Darcy law (Eq. 9) is used to describe the dynamic behavior of the porous media along the x direction, therefore $K=K_x$ while in the other directions the permeability is null.
- The Local Thermal Equilibrium (LTE) model is adopted to simulate the heat exchange between the fluid zone and solid matrix in the porous model. The fluid zone is the air and the PCM is considered as a solid zone in the porous model.
- The solid phase in the porous model takes into account the behavior of the PCM and a unique solid temperature function T_s is considered.

The governing equations for 2D porous model are presented in Cartesian coordinates:

- *Continuity equation*

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{11}$$

- *x - momentum equation*

$$\begin{aligned}\rho_f\left(\frac{1}{\varepsilon}\frac{\partial u}{\partial t}+\frac{u}{\varepsilon^2}\frac{\partial u}{\partial x}+\frac{v}{\varepsilon^2}\frac{\partial u}{\partial y}\right)&=-\frac{\partial p}{\partial x}\\ &+\frac{1}{\varepsilon}\left[\frac{\partial}{\partial x}\left(\mu_f\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_f\frac{\partial u}{\partial y}\right)\right]-\frac{\mu_f}{K_x}u\end{aligned} \tag{12}$$

- *y – momentum equation*

$$\begin{aligned}\rho_f\left(\frac{1}{\varepsilon}\frac{\partial v}{\partial t}+\frac{u}{\varepsilon^2}\frac{\partial v}{\partial x}+\frac{v}{\varepsilon^2}\frac{\partial v}{\partial y}\right)&=-\frac{\partial p}{\partial y}\\ &+\frac{1}{\varepsilon}\left[\frac{\partial}{\partial x}\left(\mu_f\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_f\frac{\partial v}{\partial y}\right)\right]-\frac{\mu_f}{K_y}v\end{aligned} \tag{13}$$

Energy equation in local thermal equilibrium (LTE) condition:

$$\begin{aligned}&(\rho c)_{eff}\frac{\partial T}{\partial t}+\rho_f c_{p,f}\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\\ &\frac{\partial}{\partial x}\left(k_1\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_2\frac{\partial T}{\partial y}\right)-\varepsilon\rho_{PCM}H_L\frac{\partial \beta}{\partial t}\end{aligned} \tag{14}$$

where the component u and v are the air velocity inside the porous model along Cartesian coordinates x and y, respectively, ρ_f is the air density, ε is the porosity of the fluid phase, p is the relative pressure, μ_f is the air dynamic viscosity, K_x and K_y are the permeability components of the porous zone, $c_{p,f}$ and k_f are respectively the air specific heat and air thermal conductibility, H_L is the latent heat of fusion. In the energy equation, for LTE assumption, $T = T_s = T_f = T_{PCM}$ [18] and, moreover, the liquid fraction β depends by the solid temperature T and the melting of the PCM is described by the last term. The effective heat transfer capacity is equal to:

$$\begin{aligned}(\rho c)_{eff}\frac{\partial T}{\partial t}+\rho_f c_{p,f}\,(\rho c)_{eff}&=\varepsilon\left(\rho c_p\right)_f\\ &+\varepsilon\left(\rho c_p\right)_{PCM}+(1-2\varepsilon)\left(\rho c_p\right)_{cord}\end{aligned} \tag{15}$$

The components of the equivalent thermal conductivity k_{eff} of porous medium are:

- Parallel for heat conduction in the longitudinal direction (along x - axis):

$$k_1=\varepsilon k_f+\varepsilon k_{PCM}+(1-2\varepsilon)k_{cord} \tag{16}$$

- Serial for heat conduction in the transversal direction (along y - axis):

$$k_2=\frac{k_{cord}k_{PCM}k_f}{\varepsilon k_{PCM}k_{cord}+\varepsilon k_f k_{cord}+(1-2\varepsilon)k_{PCM}k_f} \tag{17}$$

In irreversible process, like heat convection in a porous medium, the fluid motion due to the viscous effect and heat transfer under finite temperature gradients cause always an entropy generation. Considering Bejan [9] and the analysis proposed in [12] for PCM, the volumetric rate of entropy generation for the present problem is:

$$\begin{aligned}\dot{S}'''_{gen}&=\overbrace{\underbrace{\frac{k_1}{T^2}\left|\frac{\partial T}{\partial x}\right|^2+\frac{k_2}{T^2}\left|\frac{\partial T}{\partial y}\right|^2}_{\dot{S}'''_{gen,\Delta T,Porous}}+\varepsilon\underbrace{\frac{\rho_{PCM}H_L}{T_m}\dot{\beta}}_{\dot{S}'''_{gen,\Delta T,PCM}}}^{\dot{S}'''_{gen,\Delta T}}\\ &+\overbrace{\frac{\mu_f}{T}\phi+\frac{\mu_f}{KT}|u|^2}^{\dot{S}'''_{gen,\Delta p}}\end{aligned} \tag{18}$$

where T_m is the melting temperature, $\dot{\beta}$ is the time derivative of the liquid fraction.

The $\dot{S}'''_{gen}$ expression contains two-terms, the first term on the right-hand side is the contribution due to heat transfer irreversibility, $\dot{S}'''_{gen,\Delta T}$, while the send terms the contribution made by fluid friction irreversibility, $\dot{S}'''_{gen,\Delta p}$. In the first term on the right-hand side, two different contributions are present: one referred to the volumetric rate of entropy generation for the porous medium in LTE [19] and another referred to PCM entropy generation during the phase change material [12].

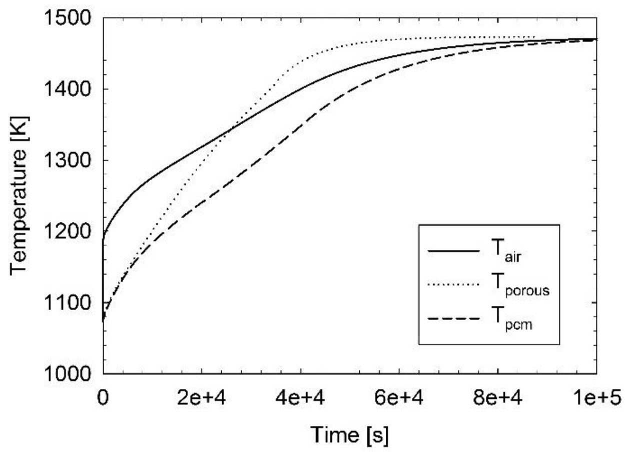
3. NUMERICAL PROCEDURE

Ansys-Fluent 15.0 is used as the computational software to solve the governing equations. A grid dependence test is carried out to choose the best grid that represents a good compromise between the computational time and the solution accuracy. The variation of temperature is monitored and the chosen mesh has 308000 cells, because the relative error with the finest grid was only 1.2%. A time step size equal to 0.5 s is considered to execute the transient analysis. The SIMPLE algorithm is employed for the pressure-velocity coupling, for the pressure calculation the PRESTO algorithm is used, for energy and momentum equation the second order upwind scheme is adopted. To calculate equations (18) a user-defined memory is implemented, in order to take into account, the entropy generation. The inlet air temperature is 1473.15 K and the initial temperature of the system is 1073.15 K.

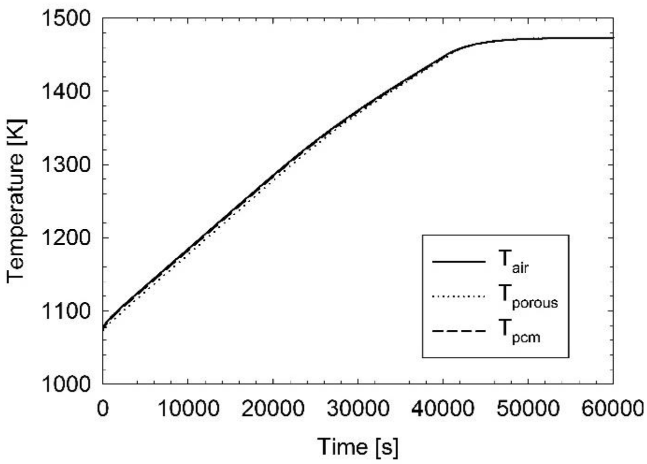
4. RESULTS AND DISCUSSION

The results are presented in term of liquid fraction, average temperature evolution and temperature profiles for different CPLs. Moreover, the entropy generation is still evaluated during the time for different CPLs. In Fig.3 is showed a comparison between the direct model and the porous media model in term of average temperature evolution during the time for parallel plates system at CPL=2 and CPL=16 plotting the PCM temperature and air Temperature of direct model and the average temperature of the porous model.

It should be declared that for higher CPL the two models (conjugate-heat-transfer approach and porous media approach) are similar. In Fig. 4 are depicted the liquid fraction, stored energy and temperature evolution for the porous media model at different CPLs.

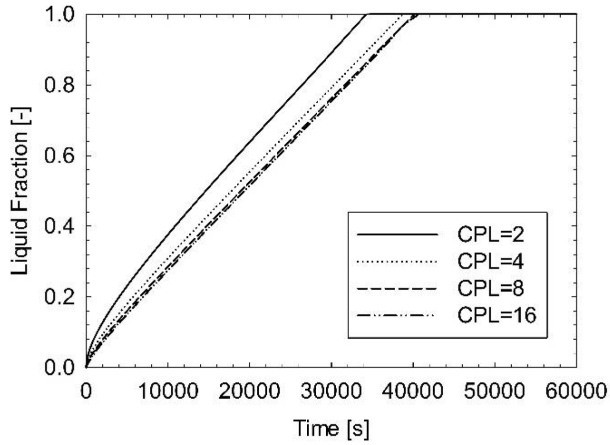


(a)

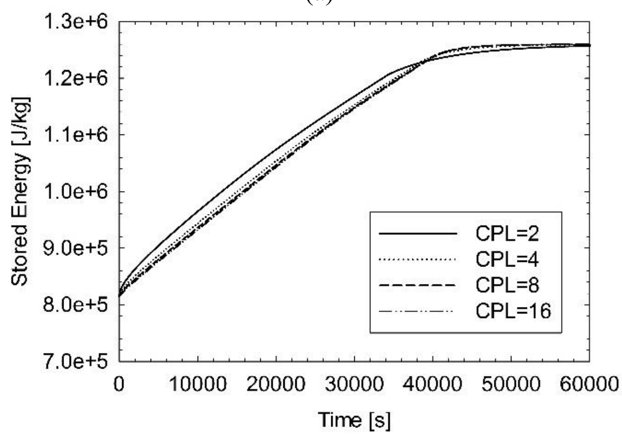


(b)

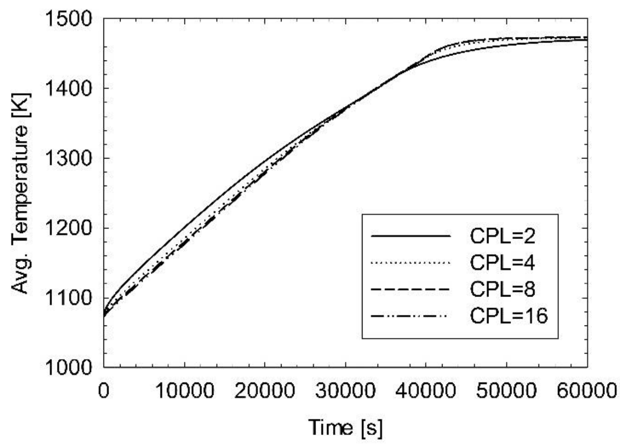
Figure 3. Comparison between the direct model and the porous model in term of Volume-Average Temperature for air, pcm and porous media during the time for different CPL: CPL=2 (a) and CPL=4 (b)



(a)



(b)



(c)

Figure 4. Volume-Average Liquid fraction (a), Average Stored Energy (b) and Volume-Average Temperature (c) as function of time for different CPLs for the porous media model

It is possible to see that lower CPLs underestimate the evolution of the liquid fraction while for higher CPL number the liquid fraction evolution is the same behavior. The entropy generation analysis is showed in fig.5 in term of thermal entropy generation, friction entropy generation, total entropy generation and Bejan Number.

There are many aspects to see: first of all, the thermal entropy generation is predominant respect to the friction entropy generation, in fact the Bejan number is always unitary; moreover, when the domain is fully liquefied, there is a slightly decrease of the Bejan Number because the systems tends to reach a thermal equilibrium with at constant temperature. Moreover, the thermal aspects of the system are constant while the CPL influences only the dynamic aspect of the system, in fact the friction entropy generation is different for various CPLs.

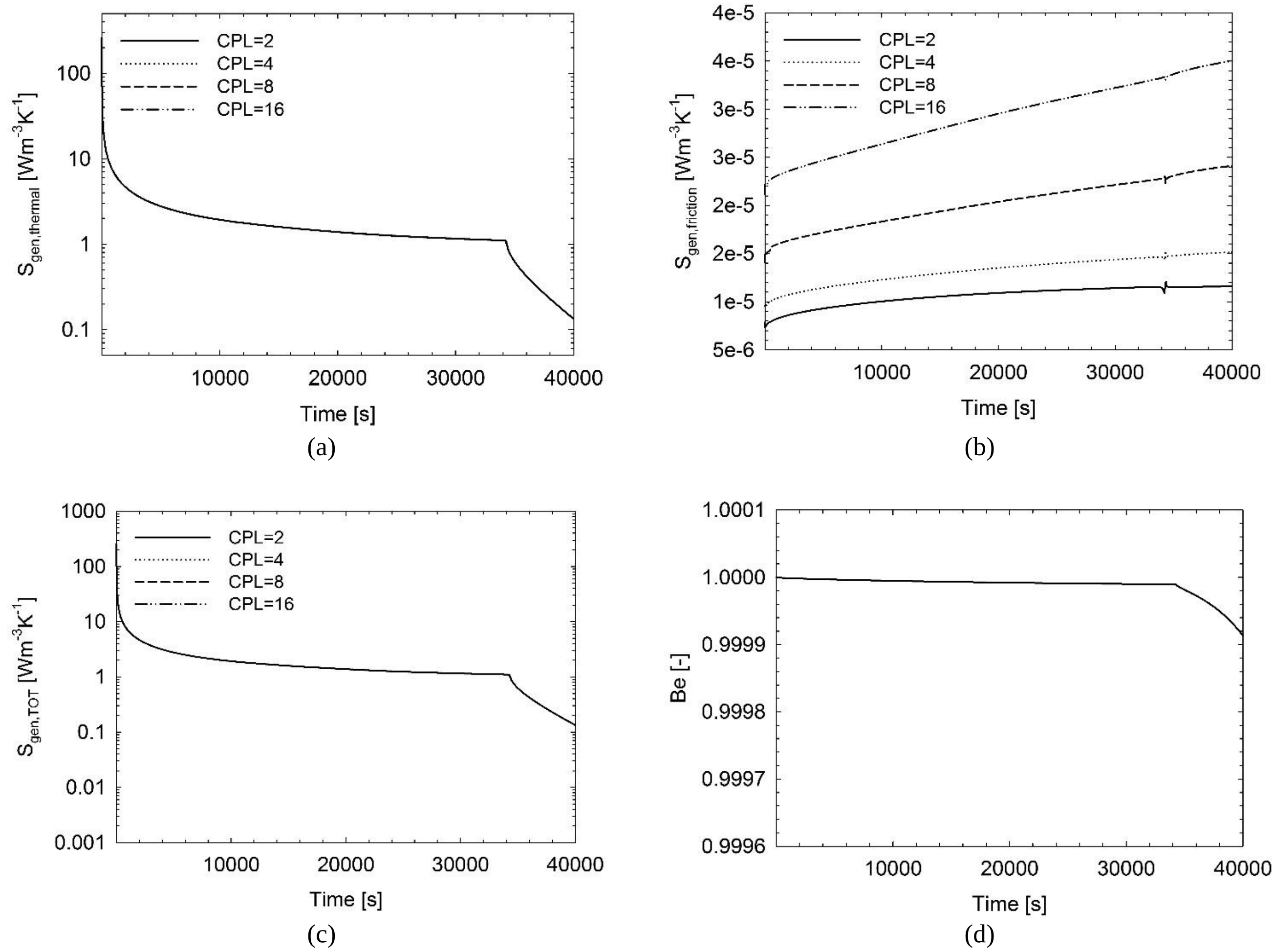


Figure 5. Entropy generation analysis in term of thermal entropy generation (a), friction entropy generation (b), total entropy generation (c) and Bejan Number(d) as function of time

5. CONCLUSIONS

A parallel plates channel system with PCM as thermal energy storage was numerically studied. A comparison between a conjugate-heat-transfer direct model and an analogous porous medium model was accomplished for different channels per unit of length (CPL). The local thermal equilibrium assumption for the porous medium was employed. The results showed that for low CPL values the two models present some significant differences while for higher CPL numbers these differences become very small. The entropy generation analysis has showed that the thermal generation analysis is predominant respect to the friction generation analysis and when the thermal equilibrium is reached, there is a slight increase of the friction entropy generation.

REFERENCES

[1] Mohamed SA, Al-Sulaiman FA, Ibrahim NI, Zahir MH, Al-Ahmed A, Saidur R, Yılbaş BS, Sahin AZ. (2017). A review on current status and challenges of inorganic phase change materials for thermal energy storage systems. Renewable and Sustainable Energy Reviews 70: 1072-1089. https://doi.org/10.1016/j.rser.2016.12.012

[2] Zhou D, Zhao CY, Tian Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. Applied Energy 92: 593-605. https://doi.org/10.1016/j.apenergy.2011.08.025

[3] Sharma SD, Sagara K. (2005). Latent heat storage materials and systems: A review. International Journal of Green Energy 2: 1–56. https://doi.org/10.1081/GE-200051299

[4] Zalba B, Marin JM, Cabeza LF, Mehling H. (2003). Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications. Applied Thermal Engineering 23: 251–283. https://doi.org/10.1016/S1359-4311(02)00192-8

[5] Kurnia JC, Sasmito AP, Jangam SV, Mujumdar AS (2013). Improved design for heat transfer performance of a novel phase change material (PCM) thermal energy storage (TES). Applied Thermal Engineering 50: 896-907. https://doi.org/10.1016/j.applthermaleng.2012.08.015

[6] Andreozzi A, Buonomo B, di Pasqua A, Ercole D, Manca O. (2017). Heat transfer behaviors of parallel plate

system in sensible thermal energy storage. Energy Procedia 126: 107-144. https://doi.org/10.1016/j.egypro.2017.08.129
[7] Iten M, Liu S, Shukla A. (2016). A review on the air-PCM-TES application for free cooling and heating in the buildings. Renewable and Sustainable Energy Reviews 61: 175-186. https://doi.org/10.1016/j.rser.2016.03.007
[8] Stathopoulos N, Mankibi ME, Santamouris M. (2017). Numerical calibration and experimental validation of a PCM-Air heat exchanger model. Applied Thermal Engineering 114: 1064-1072. https://doi.org/10.1016/j.applthermaleng. 2016.12.045
[9] Bejan A. (1996). Entropy Generation Minimization. CRC Press, Boca Raton.
[10] Jegadheeswaran S, Pohekar SD, Kousksou T. (2010). Exergy based performance evaluation of latent heat thermal storage system: A review. Renewable and Sustainable Energy Reviews 14: 2580–2595. https://doi.org/10.1016/j.rser.2010.07.051
[11] Agyenim F, Hewit N, Eames P, Smyth M. (2010). A review of materials and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renewable and Sustainable Energy Reviews 14: 615–628. https://doi.org/10.1016/j.rser.2009.10.015
[12] El-Dessouky H, Al-Juwayhel F. (1997) Effectiveness of a thermal energy storage system using phase-change materials. Energy Conversion and Management. 38: 601–617. https://doi.org/10.1016/S0196-8904(96)00072-6
[13] Wang FQ, Shuai Y, Tan HP, Yu CL. (2013). Thermal performance analysis of porous media receiver with concentrated solar irradiation. International Journal of Heat and Mass Transfer 62: 247-254. https://doi.org/10.1016/j.ijheatmasstransfer.2013.03.003
[14] Chase MW Jr. (1998). NIST-JANAF Themochemical Tables. Fourth Edition, The Journal of Physical Chemistry A Ref. Data, Monograph 9: 1-1951.
[15] Al-abidi A, Bin Mat S, Sopian K, Sulaiman MY, Mohammed ATh. (2013). CFD application for latent heat thermal energy storage: A review. Renewable and Sustainable Energy Reviews 20: 353-363. https://doi.org/10.1016/j.rser.2012.11.079
[16] Pal D, Joshi YK (1998). Thermal management of an avionics module using solid-liquid phase-change materials. Journal of Thermophysics and Heat Transfer 12: 256-262. https://doi.org/10.2514/2.6329
[17] Bahrami M, Yovanovich MM, Culham JR. (2005). Pressure drop of fully-developed, laminar flow in microchannels of arbitrary cross-section. Procedings of ICMM, ed., 3rd Int. Conf. Microch. Minich. ICMM2005-75109
[18] Nield DA. (2002). A note on the modeling of local thermal non-equilibrium in a structured porous medium. International Journal of Heat and Mass Transfer 45: 4367–4368. https://doi.org/10.1016/S0017-9310(02) 00138-2
[19] Buonomo B, Manca O, Lauriat G. (2014). Forced convection in micro-channels filled with porous media in local thermal non-equilibrium conditions. International Journal of Thermal Sciences 77: 206-222. https://doi.org/10.1016/j.ijthermalsci.2013.11.003

NOMENCLATURE

c, c_p	Specific heat, J kg^{-1} K^{-1}
H	Height of a single elementary channel, m
H_L	Latent heat of fusion, J kg^{-1}
k	Thermal conductivity, W m^{-1} K^{-1}
K	Permeability, m^2
L	Length of a parallel plate, m
n	Air Channel per unit of length (CPL)
p	Pressure, Pa
Pe	Peclet number of the channel
s	Thickness of a single elementary channel, m
$\dot{S}'''_{gen}$	volumetric rate of entropy generation, W m^{-3} K^{-1}
$\dot{S}'''_{gen,\Delta p}$	volumetric rate of entropy generation by fluid friction, W m^{-3} K^{-1}
$\dot{S}'''_{gen,\Delta T}$	volumetric rate of entropy generation by heat transfer, W m^{-3} K^{-1}
t	time, s
T	Temperature K
u	Air x-velocity component, m s^{-1}
U	Unit of length, m
v	Air y-velocity component, m s^{-1}
V	Volume, m^3
W	Width of the system, m
x	Cartesian axis direction, m
y	Cartesian axis direction, m
z	Cartesian axis direction, m

Greek symbols

α_{sf}	Area Surface density, m^2
β	Liquid fraction
ΔT	Melting range temperature, K
ρ	density, kg m^{-3}
Δp	Air Pressure drop, Pa
ε	Porosity
μ_f	Dynamic viscosity of the air, m^2 s^{-1}

Subscripts

air	air
avg	average
cord	cordierite
d	dispersion
D	Darcy
eff	effective
f	Porous fluid phase, air
m	PCM melting
PCM	Phase change material
total	packaging
n	Air Channel per unit of length (CPL)
s	Solid phase of the porous zone
x	Along *x* direction
y	Along *y* direction
z	Along *z* direction