Revue des Energies Renouvelables Vol. 19 N°3 (2016) 333 -343
DOI: https://doi.org/10.54966/jreen.v19i3.572

Numerical analysis of a latent thermal energy storage unit using two phase change materials with different melting temperatures

Fouzi Benmoussa [1 *], Hocine Benmoussa [1] and Ahmed Benzaoui [2]

[1] Faculty of Technology, Mechanics Department, University of Batna-2
1 rue Chahid Boukhlouf, Batna 05000, Algeria
[2] Faculty of Physics, University of Sciences and Technology Houari Boumedienne, USTHB
B.P. 32, 16111 Bab Ezzouar, Algiers, Algeria

(reçu le 10 Septembre 2016 - accepté le 28 Septembre 2016)

Abstract - *This study presents a mathematical model based on the enthalpy method for the transient thermal behavior of a shell-and-tube latent thermal energy storage (LTES) unit using two kinds of phase change materials (PCMs) named PCM1 and PCM2, with different melting temperatures. Numerical simulations are carried out to investigate the effects of heat transfer fluid (HTF) inlet temperatures on the unsteady temperatures and melting fractions evolution of PCM1 and PCM2 as well as the unsteady total energy stored evolution in different zone of PCMs. Charging process was studied numerically under three different HTF inlet temperatures above the melting point of the PCMs. The results shows that melting rates of PCM2 are the fastest and that of PCM1 are the slowest, the PCM2 temperature and melting fraction evolution changes rapidly with time from the start of heating process passing through the phase change period to the end of charging process. It is also found that the total energy stored gradually increases from minimum value which define the beginning of the charging cycle to maximum value defined the end of the cycle. The maximum total energy stored is observed in PCM1 with high melting temperature and high latent heats of fusion. The effects of HTF inlet temperature on the total energy stored show that heat storage capacity is large when the temperature difference between the HTF inlet temperature and the melting point of PCMs is large.*

Résumé - *Ce travail présente un modèle mathématique basé sur la formulation d'enthalpie pour décrire le processus de charge et le comportement thermique d'une unité de stockage thermique par chaleur latente constituée de deux tubes concentriques, utilisé deux matériaux à changement de phase nommés PCM1 et PCM2, avec différentes températures de fusion. Une série d'investigation numérique ont été menée dans le but d'analyser l'influence de la température d'entrée du fluide caloporteur 'HTF' sur l'évolution instationnaire de la température et la fraction de fusion des deux PCMs, ainsi que l'évolution de l'énergie thermique stockée dans différentes zones de PCMs. Le processus de stockage thermique est étudié sous l'effet de trois différentes valeurs de la température d'entrée du fluide caloporteur au-dessus de la température de fusion des PCMs. Les résultats montrent que le taux de fusion du PCM2 est plus rapide que PCM1, la température et la fraction de fusion du PCM2 varie rapidement pendant le processus de stockage passant par le changement de phase jusqu'à atteindre la température d'entrée du fluide HTF. La quantité d'énergie stockée augmente pendant le processus de stockage jusqu'à une valeur maximale à la fin du processus. Le maximum d'énergie thermique stockée est observé dans le PCM1 avec haute chaleur latente et température de fusion. L'effet de la température d'entrée du fluide HTF sur la quantité d'énergie stockée montre que la capacité de stockage thermique est importante, quand la différence entre la température d'entrée du fluide HTF et le point de fusion des PCMs est grande.*

[*] benmoussa_fouzi@yahoo.fr

Keywords: Latent thermal energy storage - Phase change materials - Storage rate - Energy stored - Numerical simulation - Enthalpy method.

1. INTRODUCTION

The latent thermal energy storage (LTES) during the melting processof phase change materials (PCMs) occurs in many applications: such as solar energy [1], hot water [2], heating and cooling of building [3, 4], electronic cooling [5, 6], etc. Compared to sensible thermal energy storage, LTES is favourable due to the high energy storage density of PCMs and isothermal phase transition during melting process. The development of LTES involves a completely understanding of the heat transfer process in PCMs when they undergo solid to liquid phase transition in the required operating conditions.

Therefore, LTES with a single PCM has gained considerable attention world wide recently. However, the PCM used in LTES systems usually has low thermal conductivity ranging from 0.1 to 0.6 $W.m^{-1}.K^{-1}$, which is a major draw-back for practical application. Therefore, efficient LTES systems are required for its development. During the past decade, the use of multiple PCMs in LTES systems was proposed by several authors in order to increase the charging and discharging rates of the units. Ait Adine *et al.* [7] presented a numerical study of a LTES unit consisting of a shell-and-tube type. The storage unit consists of an inner tube, outer tube and an annulus space filled with two PCMs, having different melting temperatures. In order to compare the thermal performances of the LTES using two PCMs and a single PCM, a mathematical model based on the conservation energy equations was developed.

Numerical results indicated that there is an optimum proportion between multiple PCMs to obtain the maximum thermal energy charging in the storage unit. Akgun *et al.* [8] analyzed the latent thermal energy storage system of the shell-and-tube type with three kinds of paraffin as PCMs. A novel tube-in-shell storage geometry was introduced and the effects of the Reynolds and Stefan numbers on the melting and solidification behaviors were examined. El Qarnia [9] developed a theoretical and numerical analysis of a coupled solar collector latent heat storage unit using three kinds of PCMs (n-octadecane, Paraffin wax and Stearic acid) to find the optimum design for a given summer climatic conditions of Marrakech city; the thermal performance of the unit during discharging process, was also studied.

Ming *et al.* [10] presented a theoretical model for the performance of a shell-and-tube LTES unit using multiple PCMs. The LTES unit consists of an inner tube, an outer tube and an annulus filled with PCMs. The melting temperatures of PCMs in the annulus decrease along the hot fluid flow direction for the charging process and increase along the cold fluid flow direction for the discharging process. Numerical simulations are carried out to investigate the effects of different multiple PCMs on the melted fraction, stored thermal energy and fluid outlet temperature of the LTES unit.

Li *et al.* [11] developed a mathematical model of shell-and-tube LTES unit of three kinds of PCMs. The LTES unit consists of an inner tube, an outer tube and an annulus filled with PCM1, PCM2 and PCM3 with different melting temperatures. Instantaneous solid-liquid interface positions and liquid fractions of PCMs as well as the effects of inlet temperatures of the HTF and lengths of the shell-and-tube LTES unit on melting times of PCMs were numerically analyzed. The results show that the melting times of PCM1, PCM2 and PCM3 decrease with increase in inlet temperatures of the HTF.

Farid *et al.* [12] have numerically and experimentally studied the transient thermal behavior of the LTES using different PCMs of different melting temperatures, with air as HTF. Results showed that, compared to the LTES using a single PCM, some improvement in the thermal performance of the LTES unit maybe achieved.

In the present study, a model for the shell-and-tube LTES unit using two kinds of PCMs named PCM1 and PCM2 with different melting temperatures (333 K and 323 K, respectively) is developed and solved numerically according to the initial and boundary conditions. Numerical simulations are carried out to investigate the effects of HTF inlet temperatures on the unsteady temperatures and melting fractions evolution of PCM1 and PCM2 as well as the unsteady total energy stored evolution in different zone of PCMs.

2. PHYSICAL MODEL AND MATHEMATICAL FORMULATIONS

2.1 Physical model

The schematic representation of the LTES unit with two PCMs is presented in figure 1**a-**, which is similar to the model used by Ait Adine *et al.* [7]. The physical model to be analysed is represented by a simple geometry shown in figure 1**b-**. The LTES unit consists of an inner tube, an outertube and an annulus filled with two kinds of PCMs named PCM1 and PCM2, having different melting temperatures (333 K and 323 K, respectively). The dimensions of the unitary: $L_1 = 0.47$ m, $L_2 = 0.53$ m, $R_i = 0.635$ cm and $R_o = 1.135$ cm. Initially, PCMs are solids and their temperatures are assumed to be equal to 303 K. The outer tube is well insulated and the multiple PCMs are separated by thermal thin wall. A fluid (water) flows through the inner tube and exchanges heat with PCMs . During charging process, hot water circulates in the direction of the melting temperature increase. The thermo-physical properties of the HTF and PCMs are listed in **Table 1** [13, 14]. The melting of the PCMs is studied numerically under three different HTF inlet temperatures above the melting point of the PCMs (338 K, 343 K and 353 K). The HTF mass flow rate was maintained constant during the numerical test to a value of 0.0005 kg/s.

Table 1: Thermo-Physical properties of the HTF and PCMs

	HTF	PCM1	PCM2
Fusion temperature, K	373	333	323
Latent heat of fusion, kJ/kg	$3.34.10^2$	$2.09.10^2$	$2.00.10^2$
Thermal conductivity, W/m.K	0.62	0.4	0.4
Specific heat, J/kg.K	4178	1850	1650
Density, kg/m^3	995	861	848
Dynamic viscosity, kg/m.s	769.10^{-6}	$6.3.10^{-3}$	$5.6.10^{-3}$

2.2 Assumptions

In order to simplify the physical and mathematical model, the following assumptions are adopted.

- The flow is Newtonian, incompressible and fully developed dynamically;
- Water flow is considered as laminar, thus no turbulence model is required;
- The thermo-physical properties of the HTF and PCMs are independent of temperature;
- The effect of liquid PCMs natural convection is neglected;
- Heat transfer in the PCMs is only controlled by conduction;

- The outer surface of the shell side is treated as an adiabatic boundary;
- The thermal resistance of the inner tube is negligible.

2.3 Mathematical formulations

Based on the above assumptions, the LTES melting process in the shell-and-tube unit can be treated as an axisymmetric model. Theenthalpy method is used to deal with the moving boundary problem in PCMs melting process. The governing equations for the HTF and PCMs region are shown as follows [7-10-11].

■ For the HTF region

$$\left(\rho C_p\right)_f \left(\frac{\partial T_f(x,r,t)}{\partial t} + U_f(r)\frac{\partial T_f(x,r,t)}{\partial x}\right) = k_f\left(\frac{\partial^2 T_f(x,r,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T_f(x,r,t)}{\partial r}\right) \quad ...(1)$$

$$x > 0,\ 0 < r < R_i,\ t > 0$$

Where, ρ, is the density of fluid, C_p, the specific heat, U, the fluid velocity and k is the thermal conductivity.

■ For the PCMs region

$$\left(\rho C_p\right)_{pcm} \frac{\partial \theta_{pcm}(x,r,t)}{\partial t} = k_{pcm}\left(\frac{\partial^2 \theta_{pcm}(x,r,t)}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta_{pcm}(x,r,t)}{\partial r}\right)\right) - \rho_{pcm}\,\Delta H\frac{\partial f}{\partial t} \quad ...(2)$$

$$x > 0,\ R_i < r < R_0,\ t > 0$$

Where, $\theta_{pcm} = (T - T_M),\ T_M = \begin{cases} T_{M1} & L_1 \le x \le L_2 \\ T_{M2} & 0 \le x \le L_1 \end{cases}$ (3)

f is the PCMs melting fraction. The melting fraction during charging cycle is determined as:

$$\begin{Bmatrix} f = 0 & \theta < 0 & \text{Solid} \\ 0 < f < 1 & \theta = 0 & \text{Solid + Liquid} \\ f = 1 & \theta > 0 & \text{Liquid} \end{Bmatrix} \quad (4)$$

The Equation (2) is formulated by using the enthalpy method [15], in which the total enthalpy is split into sensible heat and latent heat:

$$H(T) = h(T) + \rho f\,\Delta H \quad (5)$$

Where, $h(T) = \int_{T_M}^{T} \rho C_p\, dT$ (6)

2.4 Initial and boundary conditions

■ Initial conditions

For the HTF region-

$$\begin{cases} T_f(x, 0 < r < R_i, t=0) = T_{ini} \\ U_f(x, 0 < r < R_i, t=0) = U_{ini} \end{cases} \quad (7a)$$

For the PCMs region-

$$T_{PCM1} = T_{PCM2}\left(x, R_i \le r \le R_0, t=0\right) = 303K \quad (7b)$$

■ Boundary conditions

For the HTF region-

$$\begin{cases} T_f\,(x, 0 < r < R_i, t=0) = T_{in} \\ U_f\,(x, 0 < r < R_i, t=0) = 0.004\ m/s \end{cases} \quad (8a)$$

$$\left.\frac{\partial U_f\,(x,r,t)}{\partial r}\right|_{r=0} = \left.\frac{\partial T_f\,(x,r,t)}{\partial r}\right|_{r=0} = 0 \;\; x>0,\; t>0 \quad (8b)$$

For the PCMs region-

$$\left.\frac{\partial \theta_{pcm}(x,r,t)}{\partial r}\right|_{r=R_0} = 0 \;\; x>0,\; t>0 \quad (8c)$$

$$\left.\frac{\partial \theta_{pcm1}(x,r,t)}{\partial x}\right|_{x=0} = \left.\frac{\partial \theta_{pcm2}(x,r,t)}{\partial x}\right|_{r=L_2} = 0 \;\; R_i < r < R_0,\; t>0 \quad (8d)$$

$$k_{pcm1}\left.\frac{\partial \theta_{pcm1}(x,r,t)}{\partial x}\right|_{x=L_1} = k_{pcm2}\left.\frac{\partial \theta_{pcm2}(x,r,t)}{\partial x}\right|_{r=L_1} \quad (8e)$$

$$\theta_{pcm1}\,(x = L_1, r, t)_{PCM1} = \theta_{pcm2}\,(x = L_1, r, t)_{PCM2} \quad (8f)$$

At the inner surface boundary:

$$h_f\left(T_f - T(x, r=R_i, t)\right) = -k_{pcm}\left.\frac{\partial \theta_{pcm1}(x,r,t)}{\partial r}\right|_{x=R_i} \;\; x>0,\; r<R_i,\; t>0 \quad (8g)$$

i h is local convective heat transfer coefficient (W.m^2.K)

The total energy stored capacity for each zone of PCMs during charging process of the LTES unit can be represented by the follofing expression:

$$E_{PCMi} = \int_{T_{PCMi}}^{T_{Mi}} (mC_p)_{PCMi}\, dT + (m\Delta H)_{PCMi}\; f_i + \int_{T_{PCMi}}^{T_{f,\,in}} (mC_p)_{PCMi}\, dT \quad (9)$$

$$E_{PCMi} = (mC_p)_{PCMi}\,(T_{Mi} - T_{PCMi}) + (m\Delta H)_{PCMi}\; f_i + (mC_p)_{PCMi}\,(T_{f,in} - T_{PCMi}) \quad (10)$$

The first term of the equation (10) represents the sensible heat charging (SHC) period, when each PCMs temperature increase from its initial temperatures to the phase change, the second term represents the latent heat charging (LHC) during the phase change period. The third term represents the second sensible heat charging period under a fusion form until reching the steady state.

3. NUMERICAL SOLUTION

Commercial CFD program FLUENT 6.3 was used to conduct the numerical calculations, where the finite volume method described by Patankar [16] was used.

The energy equations were discretized with the first order upwind scheme. The time integration has been performed fully implicitly and control volumes of a uniform size and constant time steps were used. The grid size used in this study was 100 (axial) × 20 (radial) and the time step was 5 s.

4. NUMERICAL RESULTS AND DISCUSSION

Before presenting the results of the parametric studies, the aim of the numerical simulations is to give an idea about the transient thermal behavior of the LTES unit during charging process, in terms of unsteady temperature and melting fraction evolutions of PCM1 and PCM2 as well as the unsteady total energy stored evolutions in different zone of PCMs.

Our first results present the variation of temperature and melting fraction respecting to time at locations $A\,(x = 0.235,\, r = 0.00885)$ m inside PCM2 and $B\,(x = 0.735, r = 0.00885)$ m inside PCM1. Our second results present the variation of total energy stored respecting to time in different zone of PCMs. Analysis has been performed for three different HTF inlet temperatures above the melting poiny of the PCMs.

4.1 Unsteady temperature evolutions of PCM1 and PCM2

Melting of the PCMs, i.e., the storing of thermal energy has been first observed. The two kinds of PCMs were initially in the solid phase; its temperatures are set to 303 K.

Figures 2 (**a-b-c**) show the variation of temperature respecting to time of PCM1 and PCM2 for three different HTF inlet temperatures. The transient thermal behavior of the LTES presents three distinct periods. During the first period, the PCMs temperature increases rapidly with time from the start of heating process to the beginning of the phase change.

The heat transfer was predominated by conduction and the material stores energy primarily by sensible heat. During the second period, the energy is mainly charged by latent heat, and the temperature evolution of PCMs keeps constant. The third period starts when all PCMs are melted. During this period, the PCMs temperature starts to increase until reaching the value of the HTF inlet temperature, the energy is charged only by sensible heat under a fusion form until reaching the steady state.

It can be seen that, the melting rates of PCM2 are the fastest and that of PCM1 are the slowest for all three different HTF inlet temperatures. The PCM2 temperature evolution increases rapidly with time during the heating process passing through the phase change period until reaching the steady state, which can be explained by the fact that the melting point of PCM2 is lower than PCM1, so the PCM2 temperature reach quickly the melting point, thus, the hot HTF circulates in the direction of the melting temperature increase of PCMs, which result that the total energy is transferred firstly to PCM2 then to PCM1.

The results show also that, with the HTF inlet temperature increase, the melting time for PCM1 and PCM2 are shorter.

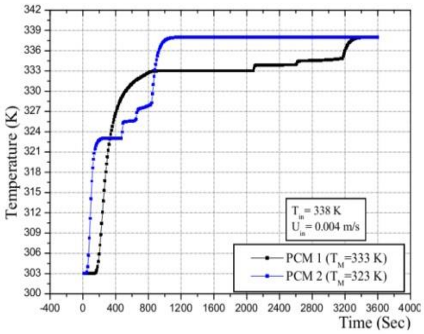

Fig. 2**a**: Unsteady temperature evolutions of PCM1 and PCM2 ($T_{f,in}$ =338 K)

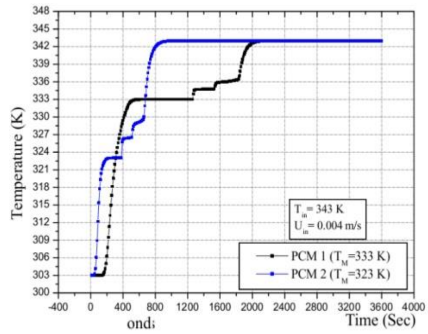

Fig. 2**b**: Unsteady temperature evolutions of PCM1 and PCM2 ($T_{f,in}$ =343 K)

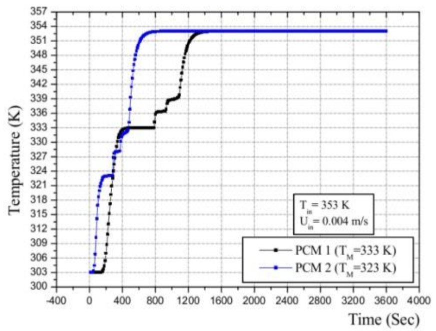

Fig. 2**c**: Unsteady temperature evolutions of PCM1 and PCM2 ($T_{f,in}$ =353 K)

4.2 Unsteady melting fraction evolutions of PCM1 and PCM2

Figures 3 (**a**-**b**-**c**)show the variation of melting fraction respecting to time of PCM1 and PCM2 for three different HTF inlet temperatures. From the figures, it can be seen that the whole LTES process can be divided into three periods:

(1) the first is sensible heat charging (SHC) period, where the PCMs temperatures is lower than melting point and the melting fraction is zero;

(2) the second is latent heat charging (LHC) period, where the PCMs temperature reaches the melting point and keeps constant, and the melting fraction increases from zero to one;

(3) the third is sensible heat charging period (SHC) again, where the PCMs have already completely melted, it’s temperatures are larger than melting point, and the melting fraction is one.

Compared to PCM1, the PCM2 melting fraction changes rapidly with time during the heating process passing through the phase change period until reaching the steady state. The same point of explanation we can notice concerning the low melting point of PCM2 and the hot HTF direction. Also when the HTF inlet temperature increases, the temperature difference between the HTF and PCMs augments which increases the heat transfer rates for both PC and PCM2; more energy is transmitted to PCM2 firstly then to PCM1, which make the first SHC and LHC periods for both PCM1 and PCM2 shortened.

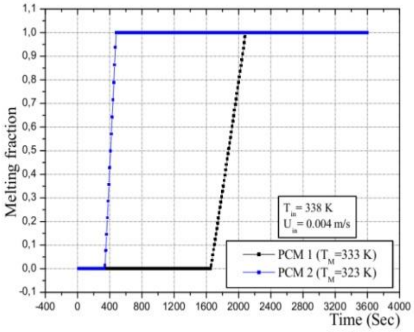

Fig. 3**a**: Unsteady melting fraction evolutions of PCM1 and PCM2 ($T_{f,in}$ =338 K)

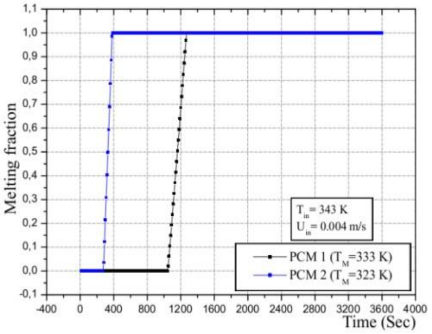

Fig. 3**b**:Unsteady melting fraction evolutions of PCM1 and PCM2 ($T_{f,in}$ =343 K)

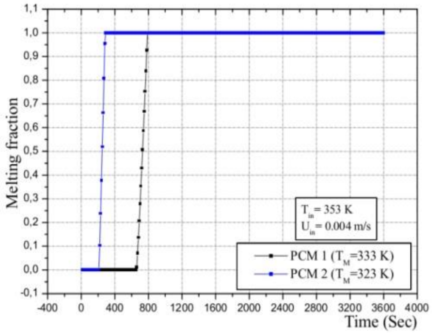

Fig. 3**c**: Unsteady melting fraction evolutions of PCM1 and PCM2 ($T_{f,in}$ =353 K)

4.3 Unsteady total energy stored evolutions in different zone of PCMs

Figures 4 (**a**-**b**-**c**) show the variation of total energy stored respecting to time in different zone of PCMs for three different HTF inlet temperatures. As shown in the figures, the total energy stored gradually increases from minimum value which define the beginning of the first SHC period to maximum value defined the end of the second SHC period.

The total energy stored reaches its maximum value, then remains constant at the end of the charging process and equals to: (281940 J/kg for PCM1 and 265630 J/kg for PCM2) for HTF inlet temperature 338 K, (291850 J/kg for PCM1 and 273880 J/kg for PCM2) for HTF inlet temperature 343 K, (310350 J/kg for PCM1 and 290380 J/kg for PCM2) for HTF inlet temperature 353 K.

When the HTF inlet temperature increases from 338 K to 353 K, the thermal energy carried by the HTF enhances, then, the heat transmitted to the PCMs becomes important and the charging process is rapidly reached. The results show also that, for each HTF inlet temperatures, the maximum energy stored is observed inPCM1with high melting temperature and high latent heats of fusion.

These results show also that, heat storage capacity is large when the temperature difference between the HTF inlet temperature and the melting point of PCMs is large.

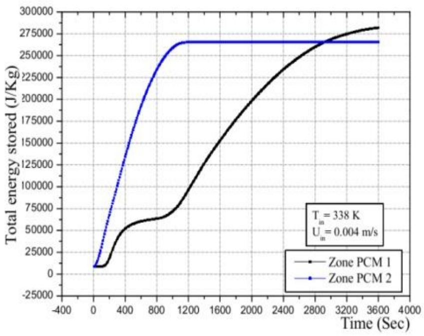

Fig. 4**a**: Unsteady total energy stored evolutions in PCM1 and PCM2 ($T_{f,in}$ =338 K)

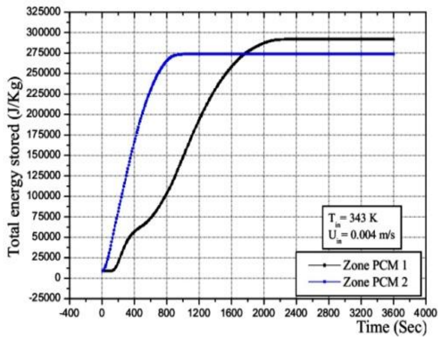

Fig. 4**b**: Unsteady total energy stored evolutions in PCM1 and PCM2 ($T_{f,in}$ =343 K)

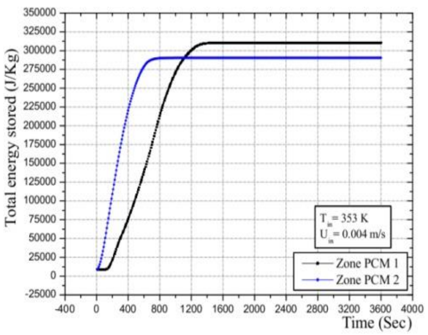

Fig. 4**c**: Unsteady total energy stored evolutions in PCM1 and PCM2 ($T_{f,in}$ =353 K)

5. CONCLUSION

Numerical investigation has been carried out in order to study the transient thermal behaviour of a shell-and-tube LTES unit using two kinds of PCMs, with different melting temperatures. After having identified the operating conditions and geometric parameters, the energy conservation equations were integrated by using the volume control approach. Several numerical simulations have been conducted in order to study the transient thermal behaviour of the unit under the effects of HTF inlet temperature. According to the results and discussions, the following conclusions can be derived:

(01) charging process has three periods for the change of temperature regarding to time in PCMs: rapidly changing period, no changing period and slowly changing period;

(02) the PCM2 temperature and melting fraction evolution changes rapidly with time from the start of heating process to the end of charging process;

(03) the hot HTF direction plays an important role on the transient thermal behavior of the unit, especially on the temperature variation of each PCMs;

(04) the total energy stored gradually increases from minimum value which define the beginning of the first SHC period to maximum value defined the end of the second SHC period;

(05) with the HTF inlet temperatures increase, the melting time for PCM1 and PCM2 are shorter;

(06) the heat storage capacity is large when the temperature difference between the HTF inlet temperature and the melting point of PCMs is large.

NOMENCLATURE

A, B	Representative locations inside PCM2, PCM1, respectively		
C_p	Specific heat J/kg.K		
E	Total energy stored J/kg		
h	Convective heat transfer coefficient $W/m^2.K$		
k	Thermal conductivity W/m.K	HTF	Heat transfer fluid
L	Length of the tube m	LTES	Latent thermal energy storage
m	Mass of the PCMs kg	PCMs	Phase change materials
Q_m	Mass flow rate kg/s	SHC/LHC	Sensible heat charging/ Latent heat charging
R_i	Inner tube radius m		
R_o	Outer tube radius m	f	Heat transfer fluid
T	Temperature K	pcm	Phase change material
T_M	Melting temperature K	in	Inlet boundary
T_{in}	Inlet temperature K	ini	Initial condition
t	Time s	ρ	Density kg/m^3
U_{in}	Inlet velocity m/s	ΔH	Latent heat of fusion kJ/kg
f	PCMs melting fraction	θ_{PCM}	Relative temperature K
		μ	Dynamic viscosity kg/m.s

REFERENCES

[1] H.E. Faith, '*Technical Assessment of Solar Thermal Energy Storage Technologies*', Renewable Energy, Vol. 14, N°1-4, pp. 35 - 40, 1998.

[2] U. Stritih, '*Heat transfer enhancement in latent heat thermal storage system for buildings*', Energy and Buildings, Vol. 35, pp. 1097-1104, 2003.

[3] Z.A. Hammou and M. Lacroix, '*A New PCM Storage System for Managing Simultaneously Solar and Electric Power*', Energy and Buildings,Vol. 38, N°3, pp. 258 - 265, 2006.

[4] Z.A. Hammou and M. Lacroix, '*A Hybrid Thermal Energy Storage System for Managing Simultaneously Solar and Electric Energy*', Energy Conversion and Management,Vol. 47, N°3, pp. 273-288, 2006.

[5] F.L. Tan and C.P. Tso, '*Cooling of Mobile Electronic Devices Using Phase Change Materials*', Applied Thermal Engineering,Vol. 24, N°2-3, pp. 159-169, 2004.

[6] S. Krishnan, S. Garimella and S. Kang, '*A Novel Hybrid Heat Sink Using Phase Change Materials for Transient Thermal Management of Electronics*', in: Engineering Joint Conference, Kohala Coast, Hawaii, March 16–20, 2003.

[7] H. Ait Adine and H. El Qarnia, '*Numerical Analysis of the Thermal Behaviour of a Shell-And-Tube Heat Storage Unit Using Phase Change Materials*', Applied Mathematical Modelling, Vol. 33, N°4, pp. 2132 - 2144, 2009.

[8] M. Akgun, O. Aydin and K. Kaygusuz, '*Thermal Energy Storage Performance of Paraffin in a Novel Tube-In-Shell System*', Applied Thermal Engineering, Vol. 28, N°5-6, pp. 405-413, 2008.

[9] H.E. Qarnia, '*Numerical Analysis of a Coupled Solar Collector Latent Heat Storage Unit Using Various Phase Change Materials for Heating the Water*', EnergyConversion and Management,Vol. 50, N°2, pp. 247 - 254, 2009.

[10] F Ming and C. Guangming, '*Effects of Different Multiple Pcms on the Performance of a Latent Thermal Energy Storage System*', Applied Thermal Engineering, Vol. 27, pp. 994 - 1000, 2007.

[11] YQ Li, YL He, HJ Song, C Xu and WW Wang, '*Numerical Analysis and Parameters Optimization of Shell-And-Tube Heat Storage Unit Using Three Phase Change Materials*', Renewable Energy, Vol. 59, pp. 92-99, 2013

[12] M.M. Farid and A. Kanzawa, '*Thermal Performance of a Heat Storage Module Using Pcms with Different Melting Temperatures: Mathematical Modeling*', Transactions of the ASME: Journal of Solar Energy Engineering, Vol. 111, pp. 152 - 157, 1989

[13] T. Watanabe, H. Kikuchi and A. Kanzawa, '*Enhancement of Charging and Discharging Rates in a Latent Heat Storage System By Use of PCM with Different Melting Temperatures*', Heat Recovery Systems & CHP, Vol. 13, pp. 57-66, 1993.

[14] L. Yang, X. Zhang and G. Xu, '*Thermal Performance of a Solar Storage Packed Bed Using Spherical Capsules Filled With PCM Having Different Melting Points*', Energy and Buildings, Vol. 68, pp. 639-646, 2014.

[15] V.R. Voller, '*Fast Implicit Finite-Difference Method for the Analysis of Phase Change Problems*', Numerical Heat Transfer, Part B- Fundamentals, Vol. 17, N°2, pp. 155 - 169, 1990.

[16] S.V. Patankar, '*Numerical Heat Transfer and Fluid Flow*', Hemisphere Publishing Corporation, New York, 1980