Numerical Analysis of the Thermal Behavior of a -Tube Heat Storage Unit Using Phase Change Materials

E.Benchara[1], and S.Ouhaibi[1] N.Bellougadia[2],K.Mansouri[2],O.Bouattane[3]
[1]Institute of Problem Solving, XYZ University, My Street, MyTown, MyCountry
SSDIA laboratory, Higher Normal School of Technic Education, Mohammedia,Morroco
elhoussinebenchara@gmail.com

Abstract : storage by latent heat systems becomes the appropriate solution in several solar heat applications. In this context, we lead the proposed study concerning the thermal storage by latent heat in a solar domestic water heater. A quantitative comparison has been developed to sort out the performances of a given unit of latent heat storage (LHS) under the effect of some physical parameters. The inlet velocity and inlet temperature of the heat transfer fluid (HTF) and geometrical parameters like the radius of the storage pipe are considered as the influent parameters in this issue. The obtained results show that the increase of the inlet velocity and temperature allows the increase of rate fusion of the PCM and reduces the fusion time. However, the increase of the radius of the pipe makes the time of fusion relatively long

Keywords: energy storage,pcm,melt frction,latent heat

1.INTRODUCTION

Phase change materials (PCM) are substances that have the ability to change phase at a certain temperature range from solid to liquid and from liquid to solid. They are characterized by a high heat of fusion (A.K. Pandey,2018). PCMs are grouped into three categories namely : organic, inorganic and eutectic PCMs (A.K. Pandey,2018), (B. Xu, P. Li, C. Chan,2015), (H. Nazir,2019). Organic PCMs are classified into paraffins, fatty acids, esters and alcohols; inorganic PCMs are classified into salts, salt hydrates, metal compounds and metal alloys; Eutectic PCMs are classified as organic-organic, organic-inorganic, and inorganic-inorganic.

In the Domain of thermal energy storage (TES), the energy can be stored in the PCM in the form of sensible heat and latent heat(B. Cárdenas, N. León,2013). So, the PCM must have higher thermal conductivity and significant latent heat. Note that latent heat storage provides higher sensible heat storage density, for a small noticeable change in temperature between the process of heat storage and release (M.M. Farid, A.M. Khudhair,2004).

Organic and inorganic materials are used for different TES systems depending on their heat of fusion and melting point in the temperature range from 0 to 120 ° C (A. Abhat ,1983). Organic PCMs are used for low and medium temperature energy storage applications, while inorganic PCMs are used for high temperature energy storage applications (S. Khare, M. Dell'Amico,2012), (M.M. Kenisarin,2010),(A. Khyad, H. Sa mrani,2016). Inorganic PCMs are used for TES applications in the range of 100°C to 900°C(B. Xu, P. Li, C. Chan ,2015). Eutectic PCMs (EPCMs) are compounds widely used for all low to medium temperature applications(H. Nazir,2018), organic-inorganic EPCM falls under medium temperature TES application with a melting point below 220 ° C, while inorganic-inorganic EPCM with slightly higher melting point is used in higher temperature TES systems. EPCMs possess the promising character of TES in the range of ambient temperature to 75 ° C. In order to reduce the energy demand, and to use solar thermal energy at night; TES systems are hybrid with solar energy, for efficient use and storage(M.H. Abokersh,2018),(G. Alva, L. Liu,,2017). TES can be treated by storage of sensible, latent or thermo-chemical heat.

The transformation of solid phase to liquid and liquid to solid is most commonly used due to their high energy storage density and high melting point (R.K. Sharma ,2015). Although solid to gas and liquid to gas PCMs are not used in TES latent heat systems due to their large volumetric change, which occurs during phase transformation. Solid to liquid PCM has many advantages such as constant melting, environmentally friendly, non-toxic nature, low vapor pressure, reliability, abundance in nature, which makes it more reliable for TES application (B. Zalba ,2003). The current energetic context has pushed scientists to think about the use of solar energy context, which has a double advantage. It is free and clean .However, the disadvantage of this source of energy is its intermittence. One of the solution considered to face this problem is energy storage. Thus, this thermal energy can be stored in the form of sensible heat or in the form of latent heat. Latent heat storage carried out in a PCM, which consists on storing the fusion energy due to the change of state of PCM and which allows its recovery at a constant temperature level during the solidification of the PCM The thermal energy can be stored isothermally thanks to the change of phase of the material. During the charging stage, the thermal energy supplied material allows its heating, and then its phase changes during the restitution of energy so that it restores the stored energy and returns to its initial state. Latent heat storage processes are generally passive storage systems, the storage material not circulate and it is separated from the heat transfer fluid, Shell-and-Tube Heat Storage Unit systems are the most promising technology in this type of storage.

In this study, a quantitative comparison has been realised using a numerical approach to assess the performances of a thermal storage unit, by latent heat. This assessment concerns the fusion time, the thermal storage rate and the melting fraction, according to some physical parameters, such as the inlet velocity, and inlet temperature of the heat transfer fluid, and geometric parameters such as the diameter of the storage pipe.

2. PHYSICAL MODEL

The physical model and operating conditions are similar as those of (Fouzi BENMOUSSA ,2016),(Hamid AitAdine,)and(Mohamed Lamine BENLEKKAM,2018). The storage unit consists of an inner tube and an outer tube filled with PCM. The outer tube is insulated, the HTF (water), flow through the inner tube with laminar flow and exchanges heat with PCM(Figure.2.1). The dimensions of the unit are given in table.2.1. The PCM used is a paraffin which proprieties are given in table 2.2.

The temperature of HTF varies in the range: T=293.15 °K and T=373.15 °K

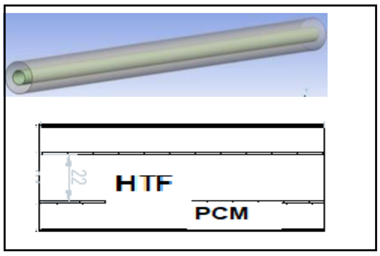

Figure 2.1.Geometric model (3D & plan)

Table 2.1.Dimensions of Storage unit

Élément	value(mm)
Inner diameter of inner tube	22
Outer diameter of inner tube	24
Inner diameter of outer tube	48
Outerdiameter of outer tube	50
Length of tubes	800

Table 2.2.Paraffin proprierties(Ali Abou Hassan,2012)

Propriety	Solid	Liquid
Melt temperature	60°C	
latent heat(Kj/Kg.°K)	213	
specific heat (Kj/Kg.°K	1.85	2.38
thermalconductivity(W/m.°K)	0.4	0.15
density (Kg/m^3)	861	778

3. GOVERNING EQUATIONS

The considered system is represented by a set of mathematical expressions to translate effectively its behavior. Let us consider the following parameters:

ρ : density(Kg/m^3)
C_p: Specific heat(J. Kg^{-1}K^{-1})
ΔH : latent heat of fusion (KJ. Kg^{-1})
T_M : fusion temperature of PCM(K)
θ: relative temperature : $T-T_M$,(K
β : liquid fraction of PCM
T_f:Temperature of fluid
T_{pcm} : temperature of PCM

To represent the different equation of the system let us consider some real assumptions:

- The fluid is incompressible and Newtonian
- The flow islaminar
- The thermophysical proprieties of PCM and HTF are constant
- The effect of natural convection for the liquid phase of the PCM is negligible
- The outer surface of the wall is adiabatic
- The wall of inner tube is thin and its material is a good thermal conductor

- Mathematical model of HTF

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

$x>0\ ;\ 0<r<R_1\ ;\ t>0$

where:

x represents axial coordinate
r represents radial coordinate
R_1 represents inner tube outer radius

-Enthalpic formulation for PCM

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

$x>0\ ;R_1<r<R_2\ ;\ t>0$

β is the liquid fraction of the PCM estimate :

$$\left\{\begin{matrix}\beta=0 & \theta<0 & \text{Solidus}\\ 0<\beta<1 & \theta=0 & \text{Solidus}+\text{liquidus}\\ \beta=1 & \theta>0 & \text{Liquidus}\end{matrix}\right\}(3)$$

-Boundary conditions for HTF

The boundary condition in this case are defined as:

$$\left\{\begin{matrix}\{U(0,r,t)=U_0 & 0<r<R_1,\ t>0\\ \left.\frac{\partial U(x,r,t)}{\partial r}\right|_{r=0}=\left.\frac{\partial T_f(x,r,t)}{\partial r}\right|_{r=0}=0 & x>0,\ t>0\end{matrix}\right. \quad (4)$$

-Boundary conditions for PCM

The boundary condition for PCM are defined as:

$$\begin{cases} \left.\dfrac{\partial T_{pcm}(x,r,t)}{\partial r}\right|_{r=R_2} = 0 \quad x>0, t>0 & (3) \\ \left.\dfrac{\partial T_{pcm}(x,r,t)}{\partial x}\right|_{x=0_2} = \left.\dfrac{\partial T_{pcm}(x,r,t)}{\partial x}\right|_{x=L_2} = 0 \quad t>0, R_1<r<R_2 & (4) \end{cases}$$

The exchange flows equation in theHTF- PCM interface is given by:

$$h_f(T_f - T(x, r = R_1, t)) = -k_{pcm} \left.\frac{\partial T_{pcm}(x,r,t)}{\partial r}\right|_{r=R_1} \quad x>0, r=R_1, t>0 \quad (5)$$

3. METHOD OF RESOLUTION

The directing equation and the boundary conditions are discretized using the finite difference method. The central difference is applied in space and the fully implicit method is applied in time.The size of the grid in the space is 0.05mm,0.03mm, and the chosen time step is Δt=1e-3 s.

The system of equations is solved iteratively using the TDMA algorithm supplemented by thedirect eliminationof backward. The result of the simulation process are represented as follows:

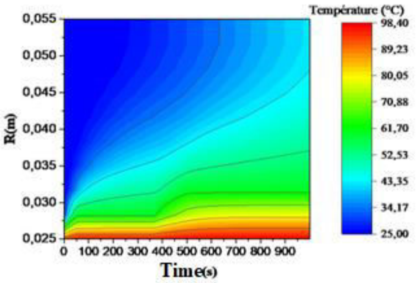

Figure 4.1. contours temperature

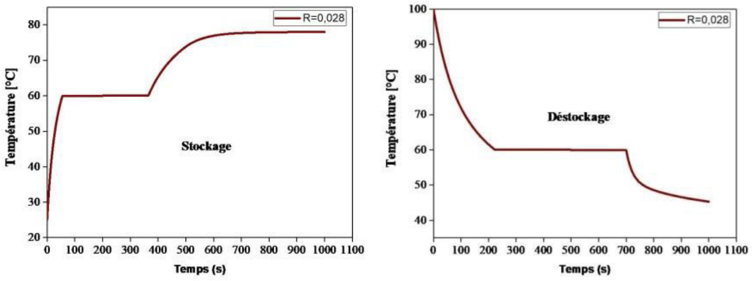

Figure 4.2.Energy storage and distockage process in the MCP, as a function of time

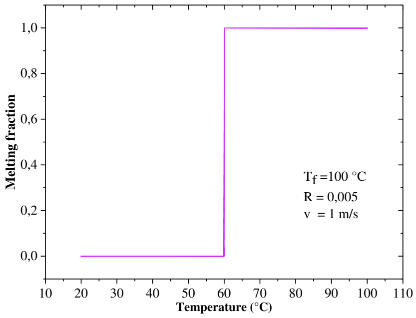

Figure 4.3. Effect of the inlet temperature of the heat transfer fluid on the melt fraction

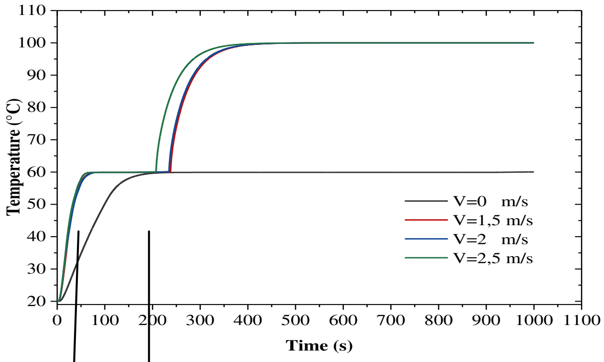

Figure 4.4.Effect of the fluid inlet speed on the melting time

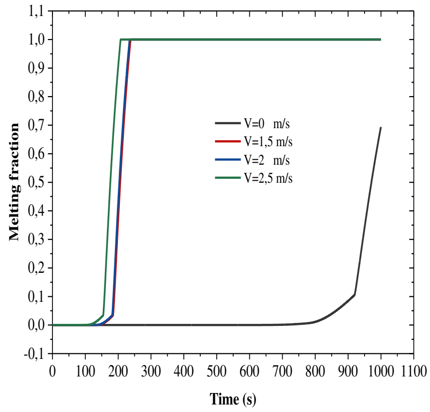

Figure 4.5.Effect of the fluid inlet speed on the melt fraction

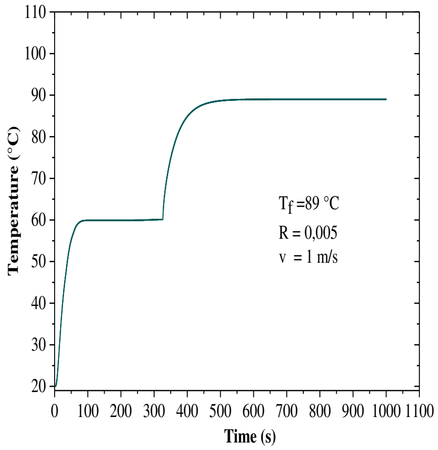

Figure 4.6.The outlet temperature of the heat transfer fluid, as a function of time

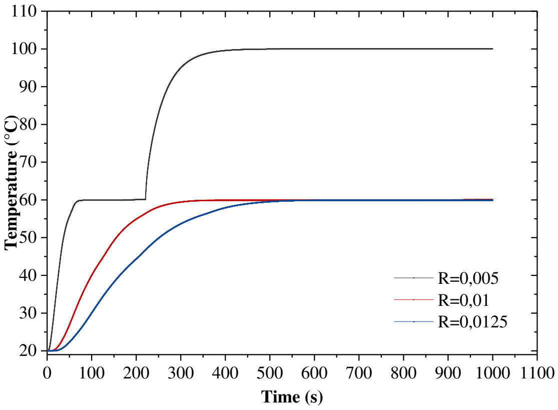

Figure 4.7. Effect of tube radius on melting time

4. DISCUSSION

This section is focused on the effects of physical and geometric parameters on the fusion time, the thermal storage rate and the melting fraction; according to the defined physical parameters, such as the inlet velocity, and inlet temperature of the heat transfer fluid, and geometric parameters such as the diameter of the storage pipe.

Thefigure 4.1.illustrates the distribution of temperature it shows that the temperature is maximum at the contact of the PCM with the heat transfer fluid tube.

In figure 4.2, we see that the solidification time of the PCM is greater than its melting time, which will allow the fluid to have enough time to heat up.

The figure 4.6 illustrates the evolution of outlet temperature; we note that this is slightly lower than the fluid inlettemperature

The figure 4.3. shows the evolution of melt fraction in function of the temperature of the HTF. We find that when the temperature reaches the melting temperature of the PCM, the fraction melting reaches 1,which means that all of the PCMin the domain has melted

The effect of the fluid inlet speed on the melting time is illustrated in figure 4.4. , we see that when the speed goes from 2m/s to 2.5m/s the fusion time goes from 2min40s to 2min 30s

Thefigure 4.5.shows that if the inlet velocity of the HTF is null, the melt fraction slowly increases to reach the maximum value of 0.7,but from a speed of 1m/s, this fraction increases rapidly to reach 1.

The Effect of tube radius on melting time is illustrated on the figure 4.7. For a large radius, the melting time is also important, and for asmall radius the fusion time increases considerably, so for a radius of 0.0125m, the fusion time is 11min40sand for a radius of 0.005m, the fusion time is 2min40swhich makes a decrease of 81.8%

5. CONCLUSION

The results show from the physical an geometric parameters studied that the melting time is considerably affected by the radius of the tube. With a reduction of the radius from 12.5mm to 5 mm, the melting time decreases by 9min therefore by82%

The inlet velocity and temperature of the HTF also have an impact on the performances of the system, the increase in the velocity and the temperature of the HTF make it possible to quickly reach a melt fraction of 1,the velocity impacted also the melting time for a variation of 0.5m/s the melting time varies from 20s

REFERENCE

A.K. Pandey, M.S. Hossain, V.V. Tyagi, N.A. Rahim, A. Jeyraj, L. Selvaraj, A. Sari. Novel approaches and recent developments on potential applications of phase change materials in solar energy. Renew. Sustain. Energy Rev., 82 (2018), pp. 281-323

B. Xu, P. Li, C. Chan, Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: a review to recent developments. Appl. Energy, 160 (2015), pp. 286-307

H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza, Ruiz, X. Xu, K. Vignarooban, P. Phelan, A.M. Kannan, Recent developments in phase change materials for energy storage applications: A review, Int. J. Heat Mass Transf., 129 (2019), pp. 491-523

B. Cárdenas, N. León, High temperature latent heat thermal energy storage: Phase change materials, design considerations and performance enhancement techniques, Renew. Sustain. Energy Rev., 27 (2013), pp. 724-737

M.M. Farid, A.M. Khudhair, S.A.K. Razack, Said Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Convers. Manag., 45 (9-10) (2004), pp. 1597-1615

A. Abhat Low temperature latent heat thermal energy storage: heat storage materials, Sol. Energy, 30 (4) (1983), pp. 313-332

S. Khare, M. Dell'Amico, C. Knight, S. Mc Garry, Selection of materials for high temperature latent heat energy storage, Sol. Energy Mater. Sol. Cells, 107 (2012), pp. 20-27

M.M. Kenisarin, High-temperature phase change materials for thermal energy storage, Renew. Sustain. Energy Rev., 14 (3) (2010), pp. 955-970.

A. Khyad, H. Samrani, M.N. Bargach, State of the art review of thermal energy storage systems using PCM operating with small temperature differences: focus on Paraffin. J. Mater. Environ. Sci., 7 (4) (2016), pp. 184-1192

H. Nazir, M. Batool, M. Ali, A.M. Kannan, Fatty acids based eutectic phase change system for thermal energy storage applications. Appl. Therm. Eng., 142 (2018), pp. 466-475

M.H. Abokersh, M. Osman, O. El-Baz, M. El-Morsi, Osama Sharaf, Review of the phase change material (PCM) usage for solar domestic water heating systems (SDWHS), Int. J. Energy Res., 42 (2) (2018), pp. 329-357

G. Alva, L. Liu, X. Huang, G. Fang, Thermal energy storage materials and systems for solar energy applications, Renew. Sustain. Energy Rev., 68 (2017), pp. 693-706

.K. Sharma, P. Ganesan, V.V. Tyagi, H.S.C. Metselaar, S.C. Sandaran, Developments in organic solid–liquid phase change materials and their applications in thermal energy storage, Energy Convers. Manage., 95 (2015), pp. 193-228

B. Zalba, J.M. Marın, L.F. Cabeza, H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Appl. Therm. Eng., 23 (3) (2003), pp. 251-283.

Fouzi BENMOUSSA, Hocine BENMOUSSA, Ahmed BENZAOUI, stockage de l’energiethermique: effet des paramètres physiques et géométriques sur les performances de stockage ,Faculté de Physique, Université des Sciences et Technologies Houari Boumediene,2016

Hamid AitAdine, Hamid El QarniaNumerical analysis of the thermal behaviour of a shell-and-tube heatstorage unit using phase change materials,Cadi Ayyad University, Faculty of Sciences Semlalia.

Mohamed Lamine BENLEKKAM, , Driss NEHARI, Nassira CHERIET,Numerical investigation of latent heat thermal energy storage system,Institute of Science and Technology University Center El Wancharissi of Tissemsilt, Algeria.2018

Ali Abou Hassan,Modélisation et caractérisation de modules de stockage de chaleur comprenant des matériaux à changement de phase,universite libanaise Ecole doctorale des sciences et de technologie,2012