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# Thermal behaviour of latent thermal energy storage unit during charging and discharging processes: effects of HTF inlet velocity

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**Abstract** - *In order to study the transient thermal behaviour of a shell-and-tube latent thermal energy storage (LTES) unit using phase change material (PCM) under variable heat transfer fluid (HTF) inlet velocities, a mathematical model based on the enthalpy formulation was developed and numerically investigated using a computational fluid dynamic. The effects of HTF inlet velocity on the transient thermal behaviour of the unit in term of PCM temperature and melting fraction evolution, as well as the unsteady total energy stored evolution are determined. The results show that charging and discharging processes have three periods for the change of temperature regarding to time in PCM: rapidly changing period, no changing period and slowly changing period. The whole LTES process during the two cycles can be divided into three periods for the change of melting fraction regarding to time in PCM: the first is sensible heat charging/discharging period; the second is latent heat charging / discharging period and the third is sensible heat charging / discharging period again. Increasing the HTF inlet velocity slowly increases the temperature and melting fraction evolution. The total energy stored gradually increase from minimum value to maximum value defined the end of the process; the amount of total energy stored under different HTF inlet velocities is the same, except the time needed for completing charging or discharging processes.*

**Résumé** - *Dans le cadre de l'étude du comportement thermique d'une unité de stockage thermique par chaleur latente constituée de deux tubes concentriques, utilise un matériau à changement de phase nommé PCM, un modèle mathématique basé sur la formulation d'enthalpie est développé, afin d'étudier l'effet de la vitesse d'entrée du fluide caloporteur HTF sur l'évolution de la température et la fraction de fusion du PCM, ainsi que l'évolution de l'énergie total stockée. Les résultats montrent que la variation de la température de PCM passe par trois périodes: période avec changement rapide, période avec sans changement et période avec changement lent. Le processus de fusion et de solidification peut être divisé en trois périodes, selon la variation de la fraction de fusion: la première est la période de stockage/déstockage par chaleur sensible; la deuxième est la période de stockage/déstockage par chaleur latente; la troisième est la période de stockage/déstockage par chaleur sensible. L'augmentation de la vitesse d'entrée du fluide caloporteur a lentement augmenté la variation de la température et la fraction de fusion. La quantité d'énergie stockée pour différente vitesse d'entrée du fluide HTF est la même, sauf le temps nécessaire pour complété le processus de stockage et déstockage.*

**Keywords**: Latent thermal energy storage - Phase change material - Heat transfer fluid - Charging and discharging processes - Melting fraction.

## 1. INTRODUCTION

Interest in utilizing clean energy sources, such as solar energy, is growing because of environmental considerations. However, due to its periodic nature, a thermal energy storage device is needed. The latent thermal energy storage (LTES) system is a very

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effective device for this purpose, because the phase change material (PCM) can absorb or release a large amount of heat during its melting or solidification process.

A wide range of studies on the thermal behaviours of the shell-and-tube LTES including PCM have been conducted by various researchers. Kibria *et al.* [1] numerically and experimentally investigated a thermal storage unit of phase change process under various flow parameters and system dimensions such as different mass flow rates, inlet temperatures of HTF and tube thicknesses. The thermal energy storage involves a shell-and-tube, where paraffin wax is used as PCM. Experimental setup has been designed to examine the physical validity of the numerical results.

Akgun *et al.* [2] experimentally investigated the melting and solidification processes of paraffin as phase change material in a shell-and-tube heat exchanger system; a series of experiments are conducted to investigate the effect of increasing the inlet temperature and the mass flow rate of the HTF both on the charging and discharging processes.

Trp *et al.* [3, 4] established a mathematical model in order to analyze the transient heat transfer phenomena of melting and solidification of paraffin wax in a cylindrical shell. They concluded that the operating conditions and geometric parameters should be chosen carefully to optimize the thermal performance of the storage unit.

Akgun *et al.* [5] analyzed the latent thermal energy storage system of the shell-and-tube type with three kinds of paraffin as PCMs. A novel tube-inshell storage geometry was introduced and the effects of the Reynolds and Stefan numbers on the melting and solidification behaviours were examined.

Lacroix [6] numerically studied the effects of temperature difference between HTF inlet temperature and melting point of PCM, HTF inlet mass flow rate on heat charging and heat discharging performance. The layout of the phase change storage unit considered consists of a shell-and-tube type. The annulus space is filled with PCM (n-octadecane). The results show that HTF inlet temperature has great effect on the time to complete heat charging or discharging cycles.

In the present study, in order to study the transient thermal behaviour of the LTES unit during both charging and discharging processes under different HTF inlet velocities, a physical and mathematical model was established for the shell-and-tube LTES unit using PCM. The simulation for the LTES process was based on the enthalpy method which takes into account phase change phenomenon. Numerical simulations are carried out in order to investigate the effects of different HTF inlet velocities on the thermal behaviour of the unit in term of PCM temperature and melting fraction evolution, as well as the unsteady total energy stored evolution.

## 2. MODEL FORMULATION

### 2.1 Physical model

The shell-and-tube PCM storage unit considered in the present study is shown in figure 1a, which is similar to the model used by Lacroix [6]. It consists of an inner tube, an outer tube and an annulus filled with PCM having melting temperature 323 K. The two-dimension physical model to be analysed is represented by a simple geometry shown in figure 1b.

HTF (water) flows through the inner tube and exchanges heat with PCM. The thermo-physical properties of the HTF and PCM are listed in **Table 1**. The dimensions of the unit are: $L = 1\,m$, $R_i = 0.635\,cm$ and $R_0 = 1.29\,cm$. Initially PCM is solid, its temperature is set to 293 K during charging process; during discharging process, PCM is liquid, its temperature is set to 353 K.

Charging and discharging processes are studied numerically under three different HTF inlet velocities (0.01 m/s, 0.05 m/s and 0.15 m/s). The HTF inlet temperature was maintained constant during charging and discharging processes to a value of 348 K and 298 K, respectively.

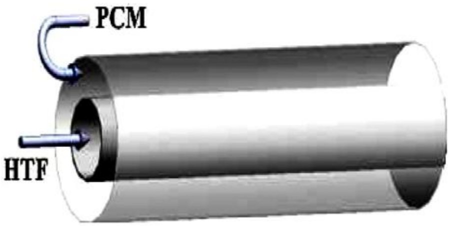


Fig. 1**a**: Schematic of the shell-and-tube latent thermal energy storage unit

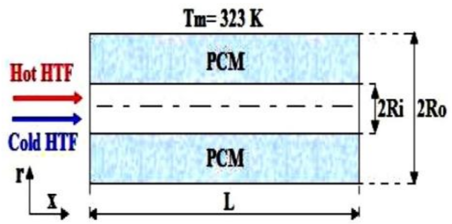


Fig. 1**b**: Physical model for numerical calculations

**Table 1**: Thermo-physical properties of the HTF and PCM [7, 8]

| | HTF (T=348 K) | HTF (T=298 K) | PCM |
|---|---|---|---|
| Fusion temperature (K) | / | / | 323 |
| Density (kg/m3) | 973 | 997 | 800 |
| Thermal conductivity (W/m.K) | 0.668 | 0.613 | 0.2 |
| Specific heat (J/kg.K) | 4195 | 4179 | 2000 |
| Latent heat of fusion (J/kg) | $334.10^3$ | $334.10^3$ | $255.10^3$ |
| Dynamic viscosity (kg/m.s) | $365.10^{-6}$ | $855.10^{-6}$ | $4.10^{-3}$ |

## 2.2 Assumptions

To develop this model, the following assumptions are made:

- The PCM is homogenous;
- The flow of HTF is Newtonian, incompressible, and a fully developed dynamically laminar flow;
- The thermo-physical properties of the HTF and PCM are independent of temperature;
- The heat loss of the unit is negligible, which means that the outer surface of the shell is thermally insulated;
- The problem is axisymmetric.

## 2.3 Gouverning equations

In formulating a mathematical model to represent this physical system, the system is divided into the following two subsections: (1) heat transfer fluid flow in the tube; (2) the region filled by the phase change material. Based on these simplifications, the thermal storage process of the LTES unit can be developed as follows.

■*For the HTF region*

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

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

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

■*For the PCM region*

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

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

$f$ is the PCM melting fraction. The melting fraction is determined as:

$$\begin{pmatrix} f=0 & \theta<0 & \text{Solid} \\ 0<f<1 & \theta<0 & \text{Solid}+\text{Liquid} \\ f=1 & \theta>0 & \text{Liquid} \end{pmatrix} \quad (3)$$

Where $\theta=(T-T_M)$

The {Eq. (2)} is formulated by using the enthalpy method (Voller [9]), in which the total enthalpy is split into sensible heat and latent heat:

$$H(T)=h(t)+\rho f\Delta H \quad (4)$$

$$\text{where, } h(T)=\int_{T_M}^{T}\rho C_p\,dT \quad (5)$$

**2.4 Initial and boundary conditions**

■ Initial conditions

*For the HTF region*

$$\begin{cases} T_f\ (x,0<r<R_i,t=0)=T_{f,ini} \\ U_f\ (x,0<r<R_i,t=0)=T_{f,ini}\end{cases}\text{, for both charging and discharging proc} \quad (6a)$$

*For the PCM region*

$$\theta_{pcm}\ (x,R_i<r<R_0,t=0)=-30K \qquad \text{During charging process} \quad (6b)$$

$$\theta_{pcm}\ (x,R_i<r<R_0,t=0)=+30K \qquad \text{During discharging process} \quad (6c)$$

■ Boundary conditions

*For the HTF region*

$$\text{Inlet boundary, }\begin{cases} T_f\ (0,r,t)=T_{f,ini} \\ U\ (0,r,t)=T_{f,ini}\end{cases} \qquad 0<r<R_i,\ t>0 \quad (7a)$$

$$\text{Symmetry axe, }\left.\frac{\partial U_f\ (x,r,t)}{\partial r}\right|_{r=0}=\left.\frac{\partial T_f\ (x,r,t)}{\partial r}\right|_{r=0}=0 \qquad x>0,t>0 \quad (7b)$$

*For the PCM region*

$$\text{Inlet and outlet boundaries, }\left.\frac{\partial\theta_{pcm}(x,r,t)}{\partial x}\right|_{x=L}=\left.\frac{\partial\theta_{pcm}(x,r,t)}{\partial x}\right|_{x=L}=0, \quad (7c)$$

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

$$\text{Outer surface boundary, }\left.\frac{\partial\theta_{pcm}(x,r,t)}{\partial r}\right|_{x=0}=0,\ \ x>0,\ t>0 \quad (7d)$$

Inner surface boundary, $$h_f\,(\theta_f - \theta(x, r = R_i, t)) = -k_{pcm} \left. \frac{\partial \theta_{pcm}(x, r, t)}{\partial r} \right|_{r=R_i} \quad (7e)$$

where, $h$ is local convective heat transfer coefficient.

The total energy stored during charging and discharging processes can be represented by the following expression:

$$E = \int_{T_{pcm}}^{T_M} m C_p \, dT + m f \Delta H + \int_{T_{pcm}}^{T_f} m C_p \, dT \quad (8)$$

$$E = m C_p (T_M - T_{pcm}) + m f \Delta H + m C_p (T_f - T_{pcm}) \quad (9)$$

The first term of the {Eq. (9)} represents the sensible heat charging period, when the PCM temperature increase from its initial temperature to the phase change, the second term represents the latent heat charging during the phase change period. The third term represents the second sensible heat charging period under a fusion form until reaching the steady state.

## 3. NUMERICAL MODELING

The melting and solidification model, which uses a commercial computational program (Fluent 6.3.26) was used to simulate the charging and discharging processes of the unit, under different HTF inlet velocities.

The two dimensions of the LTES unit were drawn and meshed in the geometric modelling and mesh generation software Gambit, which is a part of the Fluent software. Boundary layers were defined, and then the mesh was exported to the Fluent software.

The Fluent software employs the finite volume method and uses the enthalpy-porosity formulation to solve the energy equations. The energy equations were discredited with the first order upwind scheme. The grid size used in this study was 100 (axial) × 20 (radial) and the time step was 5 s.

## 4. RESULTS AND DISCUSSION

The transient thermal behaviour of the shell-and-tube LTES unit is presented in this section. A large set of numerical tests have been conducted, in order to analyze the heat transfer process under the effects of different HTF inlet velocities. The variation of temperature and melting fraction respecting to time at location $A\{x = 0.51, \; r = 0.0099\}$ m inside PCM and the variation of total energy stored in PCM under different HTF inlet velocities have been obtained by a series of numerical calculations and represented graphically.

### 4.1 Effects of HTF inlet velocity on PCM temperature evolution

The results show that charging and discharging processes have three periods for the change of temperature regarding to time in PCM.

In charging process; as shown in figure 2**a**, during the first period, the PCM temperature increases rapidly from the start of heating process to the beginning of the phase change, the PCM stores energy primarily by sensible heat.

During the second period, the energy is mainly charged by latent heat, and the temperature evolution of PCM keeps constant for a period of time.

The third period starts when all PCM is melted, during this period, the PCM temperature start to increase slowly, the energy is charged only by sensible heat under a fusion form.

In discharging process, as shown in figure 2**b**, during the first period, the PCM temperature decreases rapidly from the start of discharging process to the beginning of the phase change, the PCM delivers energy primarily by sensible heat.

During the second period, the energy is mainly discharged by latent heat, and the temperature evolution of PCM keeps constant.

The third period starts when all PCM is solidified, during this period, the PCM temperature start to decrease slowly, the energy is discharged only by sensible heat under a solidification form.

Increasing the HTF inlet velocity slowly increases the temperature evolution until the end of charging or discharging process. During the two cycles, the time period to complete the second period is within 670 s, 510 s and 470 s for HTF inlet velocity 0.01 m/s, 0.05 m/s and 0.15 m/s, respectively.

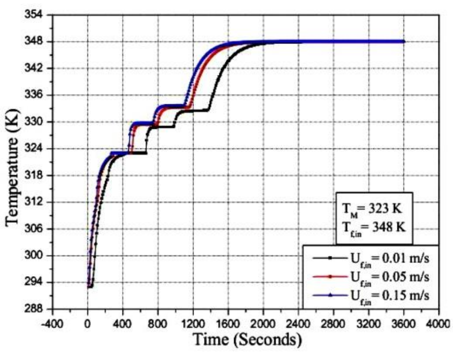


Fig. 2**a**: Effects of HTF inlet velocity on PCM temperature evolution Charging process)

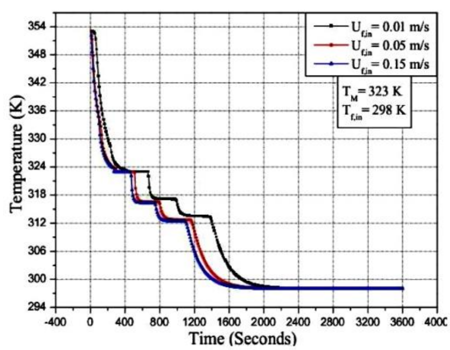


Fig. 2**b**:Effects of HTF inlet velocity on PCM temperature evolution (Discharging process)

**4.2 Effects of HTF inlet velocity on PCM melting fraction evolution**

The results show that charging and discharging processes have three periods for the change of melting fraction regarding to time in PCM.

In charging process, as shown in figure 3**a**, the first is sensible heat charging (SHC) period, where the PCM temperature is lower than melting point and the melting fraction is zero.

The second is latent heat charging (LHC) period, where the PCM temperature reaches the melting point, and the melting fraction increases from zero to one.

The third is sensible heat charging period (SHC) again, where the PCM have already completely melted, its temperature is larger than melting point, and the melting fraction is one.

In discharging process, as shown in figure 3**b**, the first is sensible heat discharging (SHD) period, where the PCM temperature is higher than melting point and the melting fraction is one.

The second is latent heat discharging (LHD) period, where the PCM temperature reaches the melting point, and the melting fraction decreases from one to zero.

The third is sensible heat discharging period (SHD) again, where the PCM have already completely solidified, its temperature is smaller than melting point, and the melting fraction is zero.

Increasing the HTF inlet velocity slowly increases the melting fraction evolution until the end of charging or discharging process. During the two cycles, the time period to complete the first sensible heat charging or discharging period is within 430 s, 300 s and 270 s for HTF inlet velocity 0.01 m/s, 0.05 m/s and 0.15 m/s, respectively.

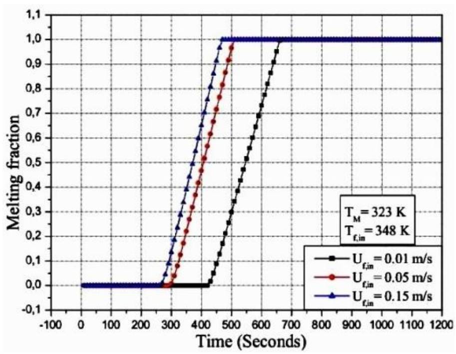


Fig. 3**a**: Effects of HTF inlet velocity on PCM melting fraction evolution (Charging process)

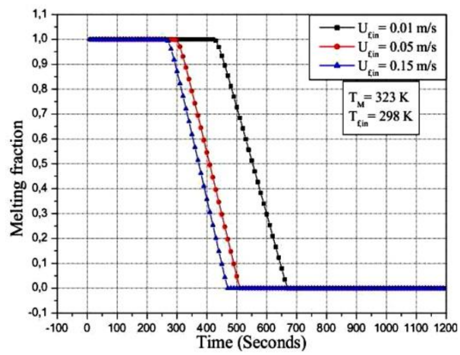


Fig. 3**b**: Effects of HTF inlet velocity on PCM melting fraction evolution (Discharging process)

### 4.3 Effects of HTF inlet velocity on total energy stored evolution

In charging process, as shown in figure 4**a**, for all values of HTF inlet velocity, 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.

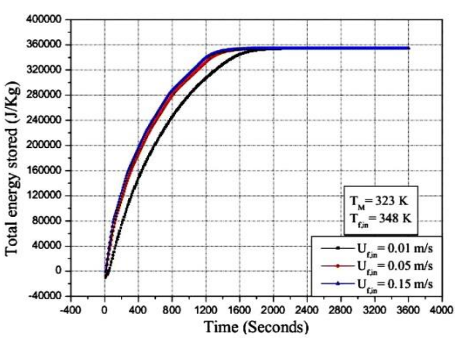


Fig. 4**a**: Effects of HTF inlet velocity on total energy stored evolution (Charging process)

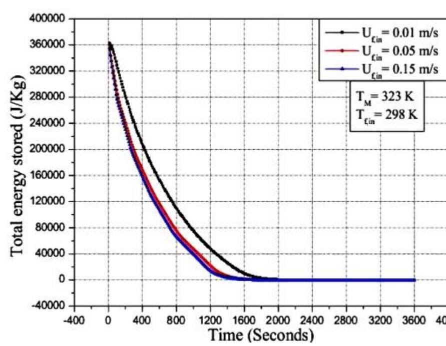


Fig. 4**b**: Effects of HTF inlet velocity on total energy stored evolution (Discharging process)

The total energy stored reaches its maximum value, then remains constant and equals 354570 J/kg for all values of HTF inlet velocity.

In discharging process, as shown in figure 4**b**, the maximum value of total energy stored to be recovered by HTF is the same as that of charging process under all three different HTF inlet velocities.

The total energy stored gradually decreases from maximum value which define the beginning of the first SHD period to minimum value defined the end of the second SHD period.

Reflected in the figures, for all numerical tests, the amount of total energy stored under different HTF inlet velocities is the same, except the time needed for completing charging or discharging processes.

## 5. CONCLUSIONS

A two dimensional CFD model based on the enthalpy method was developed in order to study the transient thermal behaviour of a shell-and-tube latent thermal energy storage unit during both charging and discharging processes.

A variety of numerical tests were conducted in order to analyze the effect of different HTF inlet velocity on the unsteady temperature and melting fraction evolution of PCM, as well as the unsteady total energy stored evolution. According to the results and discussions, the following conclusions can be derived:

**(01)** the transient thermal behaviour of the unit during the two cycles show three distinct periods for the change of PCM temperature and melting fraction regarding to time.

**(02)** increasing the HTF inlet velocity slowly increases the temperature and melting fraction evolution until the end of charging or discharging process.

**(03)** the amount of total energy stored under different HTF inlet velocities is the same, except the time needed for completing charging or discharging processes.

## NOMENCLATURE

| | |
|---|---|
| A , Representative locationsinside PCM | $C_p$ , Specific heat J/kg.K |
| E , Total energy stored J/kg | h , Convective heat transfer coefficient |
| k , Thermal conductivity W/m.K | L , Length of the tube m |
| m , Mass of the PVMs kg | R , Radius m |
| $T_M$ , Melting temperature K | $T_{in}$ , Inlet temperature K |
| T , Temperature K | f , PCMs melting fraction |
| t , Time s | μ , Dynamic viscosity kg/m.s |
| $U_{in}$ , Inlet velocity m/s | ρ , Density kg/m$^3$ |
| ΔH , Latent heat of fusion kJ/kg | $\theta_{PCM}$ , Relative temperature K |
| HTF, Heat transfer fluid | LTES Latent thermal energy storage |
| SHC/LHC, Sensible heat charging/ Latent heat charging | SHD/LHD, Sensible heat discharging/ Latent heat discharging |
| PCM, Phase change material | f , Heat transfer fluid |
| ini , Initial condition | in , Inlet boundary |

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