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STUDY OF A THERMAL ENERGY STORAGE SYSTEM USING THE LATTICE BOLTZMANN METHOD

Oussama El Mhamdi$^{(1)}$ *, Soumia Addakiri$^{(1)}$, ElAlami Semma$^{(1)}$, Mustapha El Alami $^{(2)}$
$^{(1)}$ Laboratory of engineering industrial management and innovation, University Hassan 1st, FST Settat, Morocco
$^{(2)}$ LPMMAT Laboratory, Physics department, Faculty of Sciences Ain Chok, Hassan II University, Casablanca, Morocco
*Correspondence author: Email: oussama.elmhamdi@gmail.com

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ABSTRACT

Thermal energy storage (TES) systems are much preferred in many engineering applications, which have the ability to overcome the mismatch between energy supply and energy demand. TES can be used to store thermo-chemical, sensible, or latent heat or a combination of these. Among the three forms, latent heat thermal energy storage (LHTES) has grown considerably in importance over recent years as a promising alternative to traditional systems. These systems use phase change materials (PCM), in simple or cascade configuration, and store the latent heat of melting (charging process) and release it during solidification (discharging process).

Among different configurations of LHTES systems, tube and shell heat exchangers represent a promising and simple design in high temperature PCM. In this paper, we present a new numerical study involving a tube and shell heat exchanger to evaluate the heat storage phenomena. A case study and numerical results are provided using the Lattice Boltzmann Method.

NOMENCLATURE

f_i	distribution function in the ith direction
f_i^{eq}	equilibrium distribution function in the ith direction
e_i	discrete velocity in the ith direction
t	time
δt	time step
τ	relaxation time
μ	Viscosity
g	gravitational acceleration
β	coefficient of thermal expansion
ω_i	weighting coefficient in the ith direction
c_s	Sound celerity
ρ	density
T	temperature
H	enthalpy
Fo	Fourrier number
th	Fin thickness

INTRODUCTION

The phenomena of solid-liquid phase change have attracted considerable attention in research due to their importance in a wide variety of natural and engineered systems. Applications include thermal energy storage, welding and casting for a manufacturing process, melting and freezing of soils, artificial freezing of soil for construction and mining purposes.

Recent projections predict that primary energy consumption will increase by 48% in 2040. On the other hand, the depletion of fossil resources in addition to their negative impact on the environment has accelerated the transition to sustainable energy sources.. Renewable energies such as solar radiation, ocean waves, wind and biogas have played a major role in reforming the natural balance and meeting the needs of the growing demand of the population. However, due to the vagaries of the weather, the means to store these types of renewable energies have become urgent. This has led to the need to develop efficient and sustainable methods of energy storage such as Thermal Energy Storage.

Thermal energy storage (TES) is a technology that stores thermal energy by heating or cooling a storage medium so that the stored energy can be used later for heating and cooling applications or for producing electric energy. TES systems are used in particular in buildings and in industrial processes. The benefits of using TES in an energy system include an increase in overall efficiency and better reliability, and this can lead to better economy, reduced investment and running costs, and less pollution of the environment.

TES includes Latent Heat Storage (LHS). That Latent heat builds up in a material during the phase change process and can be defined as the energy required for a phase change. The LHS system uses the energy absorbed or released during the isothermal phase change of materials. A Phase Change Material PCM) is a substance with a high heat of melting which, through melting and solidifying at a certain temperature, is able to store and release large amounts of energy.This type of TES has been the subject of many research works [1-6].

In this paper, we present a new numerical study involving a finned tube and shell heat exchanger to investigate the effect of fins dimensions on melting time and to evaluate the heat storage phenomena (charging and discharging),

PROBLEM CONFIGURATION AND MODELS

Problem configuration

The geometric configuration of the LHTES (Latent Heat Thermal Energy Storage) is shown in figure (1). Heat Transfer Fluid (HTF)flows through the inner tube from top to bottom and the outer tube is filled with PCM material. The outer cavity has metal fins for better heat diffusion through the PCM.

During the charging process, hot fluid at constant temperature circulates through the inner tube while cold fluid at constant temperature circulates through the inner tube during the discharge process.

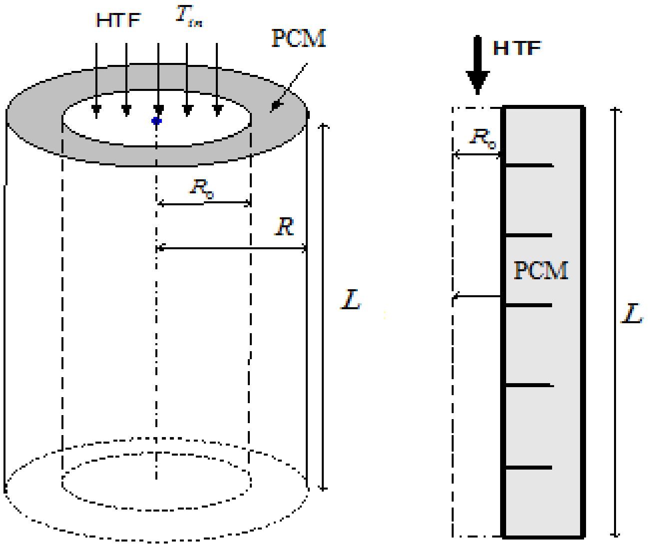

Figure 1
Heat exchanger configuration

Mathematical model

The enthalpy model is used to model the phase change process of PCM. Boussinesq's approximation is used. The model assumes that the density of the fluid is constant in all terms of the momentum equation except the force of gravity term. The governing equations for a two dimensional laminar and newtonian flow are as follows:

- Conservation of mass:

$$\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} = 0 \tag{1}$$

- Conservation of momentum

$$\rho\frac{\partial u_z}{\partial t} + \rho u_r\frac{\partial u_z}{\partial r} + \rho u_z\frac{\partial u_z}{\partial z} = \frac{\partial \rho}{\partial r} + \mu\left(\frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r} + \frac{\partial^2 u_z}{\partial z^2}\right) + \rho g\beta(T - T_{ref}) \tag{2}$$

$$\rho \frac{\partial u_r}{\partial t} + \rho u_r \frac{\partial u_r}{\partial r} + \rho u_z \frac{\partial u_r}{\partial z} = -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} + \frac{\partial^2 u_r}{\partial z^2} - \frac{u_r}{r^2} \right) \tag{3}$$

- Conservation of energy

$$\rho \frac{\partial \rho H}{\partial t} + u_r \frac{\partial \rho C_p T}{\partial r} + u_z \frac{\partial \rho C_p T}{\partial z} = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right] \tag{4}$$

H is the sum of the sensible enthalpy C_pT and the latent enthalpy f_lL. The total enthalpy *H* is resolved by the Boltzmann lattice method then the temperature can be determined from the total enthalpy. the relative length of the fins is defined by the ratio:

$$l_f = \frac{length\ of\ the\ fin}{R - R_0}$$

Axisymmetric Lattice Boltzmann model

The axisymmetric LB model for mass transport proposed in [7], is based on Boltzmann's axisymmetric equation. The Lattice Boltzmann model based on the kinetic theory proposed by Guo et al. [8] evolves as follows:

$$f_i(\mathbf{x} + \mathbf{e}_i\delta_t, t + \delta_t) = f_i(\mathbf{x}, t) + \frac{1}{\tau}\left(f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t) \right) + \delta_t \frac{1}{2}\left(F_i(\mathbf{x}, t) + F_i(\mathbf{x} + \mathbf{e}_i\delta_t, t + \delta_t) \right) \tag{5}$$

Where:

$$f_i^{eq}(\mathbf{x}, t) = r\rho\omega_i \left[1 + \frac{\mathbf{e}_i.\mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_i.\mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u}^2}{2c_s^2} \right] \tag{6}$$

With $u = (u_r, u_z)$ the velocity vector with the radial and vertical components and ω_i the weighting coefficients of the D2Q9 model namely, $\omega_0 = 4/9$, $\omega_{1,2,3,4} = 1/9$ and $\omega_{5,6,7.8} = 1/36$.
The source term $F_i(x,t)$ takes into account the axisymmetric effects and the effects of external forces:

$$F_i(\mathbf{x}, t) = \rho\omega_i \left[\left(c_s^2 - \frac{2\nu u_r}{r} \right)\frac{e_{ir}}{c_s^2} + \frac{\mathbf{u}.\mathbf{e}_i}{c_s^2} e_{ir} - u_r \right] + r\rho\omega_i \frac{(\mathbf{e}_i\text{-}\mathbf{u}).\mathbf{a}}{c_s^4} \tag{7}$$

RESULTS AND DISCUSSION

Effect of fins' dimensions

Effect of finslength

In this section, we evaluate the effect of the fins by comparing with the reference case without fins. Figure (2) shows the effect of fin length on melting time. For sizes less than 25%, we notice a small improvement for the weak liquid fractions which reaches 10% for $l_f = 0.25$. This improvement drops off as we approach full melting and becomes very small. On the other hand, for sizes that exceed 50% of the height of the liquid zone, we notice a significant gain in melting time which sometimes exceeds 30% for a liquid fraction of 90%. Thus, a height of 85% of that of the fluid zone can be considered as the optimum size giving an acceptable gain in melting time

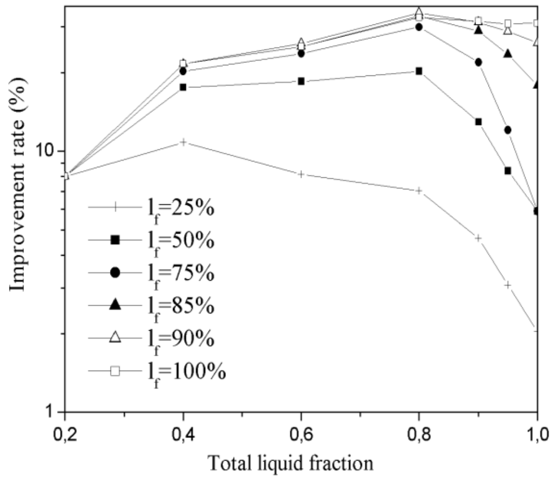

Figure 2
Improvement rate of melting for different lengths of fin

On the other hand, the heat transfer performance can also be observed in figure (3) which describes the evolution of the mean Nusselt number as a function of time for different fins length. The heat flux through the vertical walls decreases as the melting time progresses. A sharp drop in heat exchange is present at the start of the melting process, and heat transfer is carried out by thermal conduction. Over time, the fluid zone becomes larger with the development of natural convection, resulting in a marked increase in heat transfer. This phenomenon is well identified for sizes greater than 50% (85% and 100%).

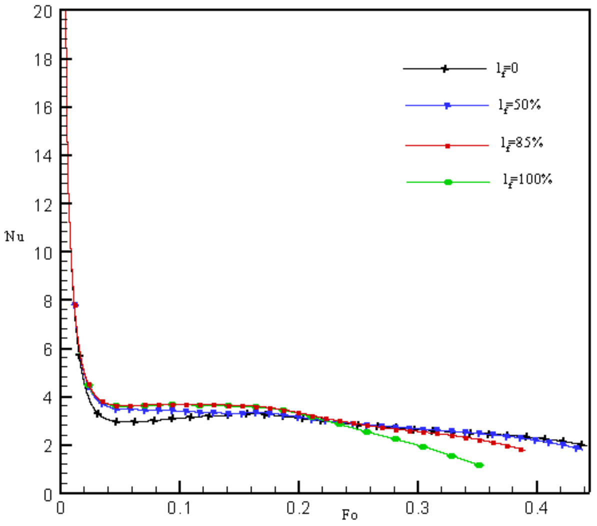

Figure 3
Evolution of Nusselt number as a function of time

Effect of fins thickness

Increasing the thickness of the fin increases the contact area between the fin and the heating tube and reduces the resistance to heat transfer; this will certainly increase the melting speed of the phase change material and thus reduce the overall melting time.

To study the effect of fin thickness on the performance of the system, we considered a system with 3 fins. Figure (4) shows the variation of the total melting time as a function of the thickness.

The increased fin thickness allows more heat to be transferred to the PCM. Indeed the contribution of the increase in thickness in the acceleration of the melting process is quite clear for thicknesses less than 0.09. Beyond this value, the improvement in the melting time remains limited. On the other hand, increasing the thickness requires more mass of metal with a larger aspect ratio for the same mass of the PCM. Thus, a technical and economic study is necessary for the correct choice of the thickness of the fins. The quantitative effect of thickness on melting time can be given by the following expression:

$$t_m = th^{-0.417} \tag{8}$$

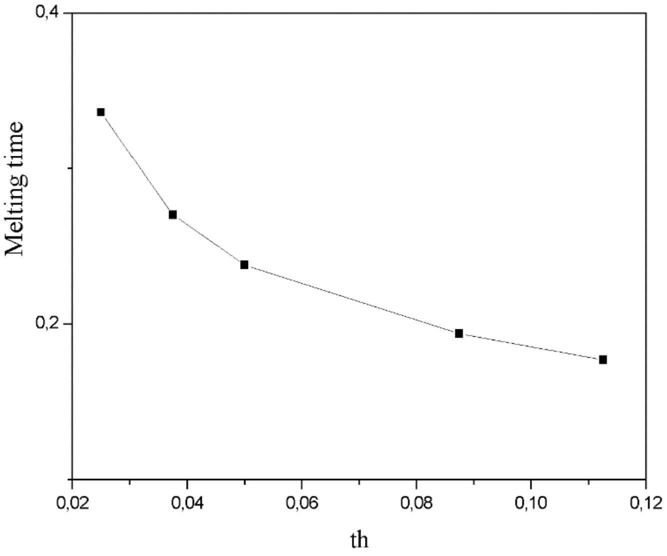

Figure 4
Melting time as a function of thickness, 3 fins

Charging and discharging

Natural convection occurs in the molten PCM and is controlled by the T_H-T_m thermal gradient. However, during solidification, the phase change is managed by the discharge temperature T_C-T_m. If during melting the natural convection is a main mechanism that influences the evolution of the liquid fraction, during solidification the natural convection becomes just an initial condition of the problem.

In this section, we carry out the discharge processes after the melting of a part of the PCM corresponding to l_f=0.25, 0.5, 0.75, 0.9 and 1. We present in figure (5), the temporal evolution of the total liquid fraction for different initial discharge conditions.
For a complete cycle corresponding to a complete melting of the PCM, the melting time is Fo = 0.445, At this point solidification begins and the liquid

fraction begins to decrease until complete solidification of the PCM corresponding to Fo = 1.

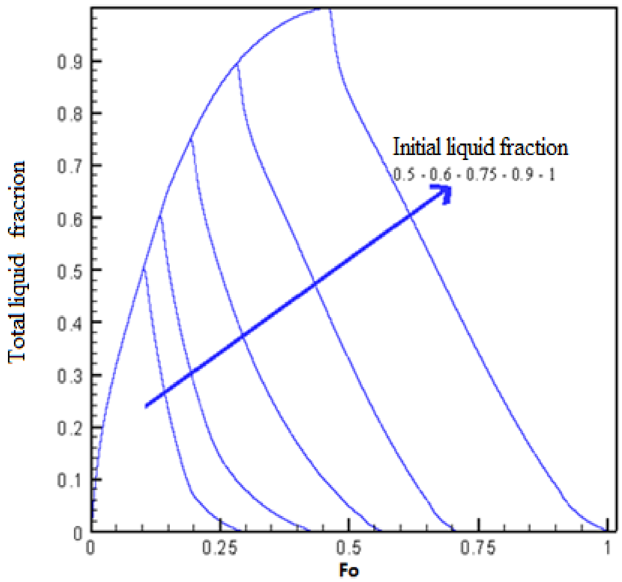

Figure 5
Total liquid fraction evolution for different initial conditions

The rate of solidification quantified by $\frac{df_l}{dt}$ is almost constant during almost the entire solidification process for each case. This uniformity of the process indicates that the flow of natural convection disappears quickly during solidification, and conduction remains the only heat transfer mechanism. For solidification from partial melting, upon discharge a second solidification front begins to propagate from the left side of the cavity.

The relative solidification time calculated as the ratio of the solidification time to the total time of a cycle is shown in figure (6). We note that the solidification time is always longer than the melting time. This difference is due to the contribution of convection in the acceleration of the melting. The relative time reaches a maximum for an initial liquid fraction of 0.6.

The increase in the exchange surface with the PCM by adding of fins improves the overall melting time. The effect of the number of fins on the behavior of the PCM during a charge-discharge cycle is studied. Figure (7) shows the evolution of the relative discharge time for numbers of fins equal to 0 - 1 - 2 - 3 - 4 - 8 - 12.

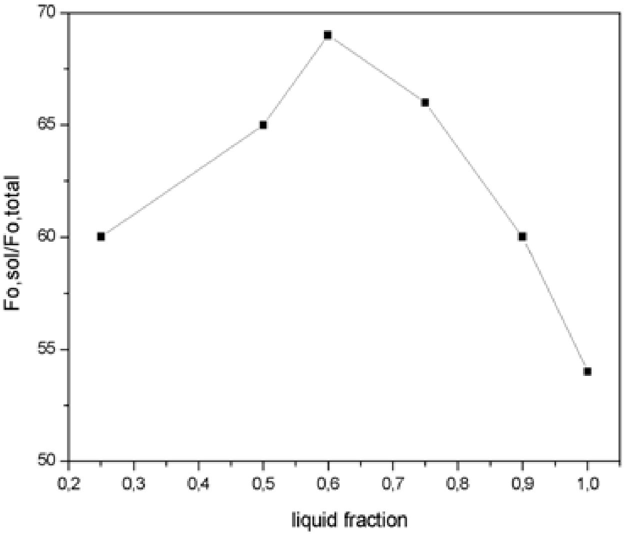

Figure 6
Evolution of relative solidification time in function of liquid fraction

In all of the cases studied, the discharge time is greater than the charge time and the discharge speed is practically constant and depends mainly on the number of fins. The relative discharge time reaches a minimum for n = 2, and increases for n> 2.

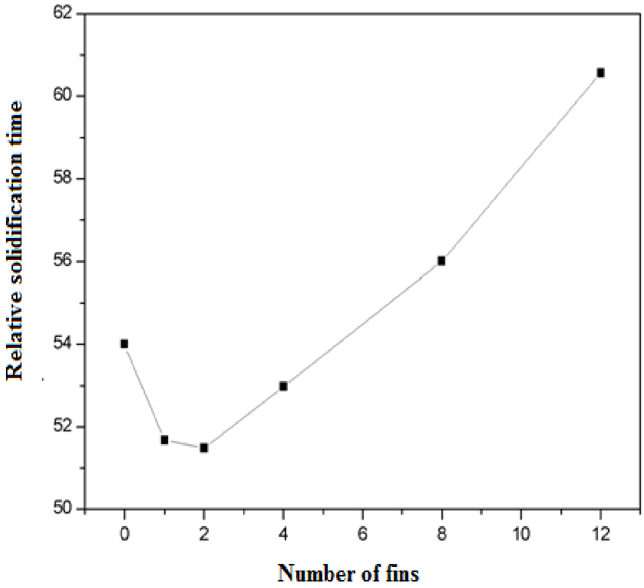

Figure 7
Evolution of relative solidification time in function of the number of fins

Figure (8) shows the variation of the outlet temperature over time. During the first phase of melting, the outlet temperature decreases with the addition of fins because of the large heat exchange surface with the MCP. During discharge, the outlet temperature changes in a smoother way and its behavior depends strongly on the number of fins.

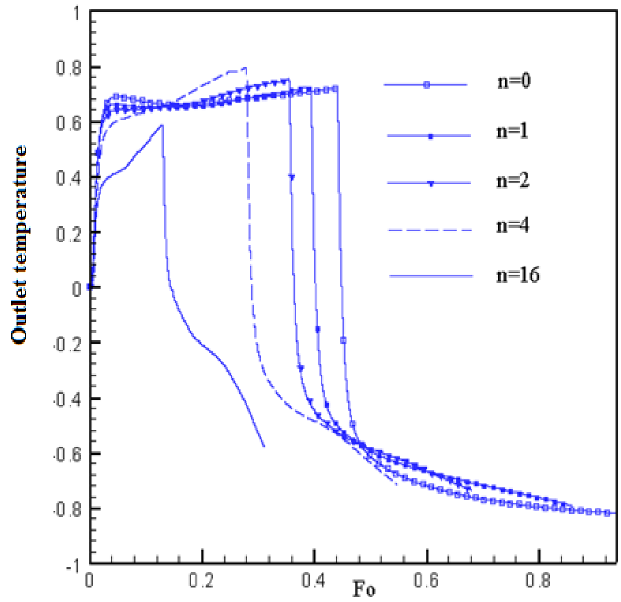

Figure 5
Outlet temperature during charging and discharging for different number of fins.

CONCLUSIONS

In this paper, we studied a finned heat exchanger. We investigate the effect of fins dimensions on the melting time, as well as charging and discharging phenomena.
The conclusions are the following:

- Adding fins accelerates the melting process. We found out that optimal values for the fins' dimensions can be set at 85% of the PCM for the length, and 0.09 for thickness.
- Discharging process takes always longer than charging process due to the absence of natural convection effect.

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