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Numerical study of thermal behavior of different cavity section incorporates a phase change material

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ABSTRACT

In this work, and in order to improve the thermal execution in building equipment, a numerical simulation of unsteady state heat transfer in three configurations of cavity section is presented to study phase change process of PCM (*Phase Change Materials*). These configurations are: square, cylindrical and elliptical cavities, which are tested for different thickness. Hence, the present work out to determinate the effect of the configuration and PCM thickness of the cavity section on the thermal behavior during the melting/solidification process. Investigations are based the enthalpy method, using CFD (computational fluid dynamics) code to track the melting/solidification process. The comparison between the numerical results and the experimental data of literature shows a good agreement. The results found that the elliptical cavity section with 10 mm thickness of PCM improve significantly the performance the building equipment.

1. INTRODUCTION

There are many types of thermal energy storage systems, latent heat thermal energy storage is the most attractive due to its high thermal storage density within limited range or constant temperature [1]. Among of these systems, the building equipment which are need a height thermal performance, especially in the hot zones. PCMs systems can store 5 to 14 times more heat per unit volume compared to sensible heat storage materials like rock or water [2]. Thermal storage systems with phase change materials offer storage of high thermal energy allowing to the designer to develop more new systems with less heat losses and high efficiency.

Recently, phase change material (PCMs) applied in several applications such in building; integration of phase change material in the building walls can reduce the high energy consumption due to heating and air conditioning systems. Therefore, they can improve the energy efficiency. Several studies have focused on characterization and classification of phase change materials (PCMs), optimization and design systems, latent heat thermal energy storage applications and heat exchange improvement [3-8]. Integration of PCMs in building envelope are destined to increase heat storage capacity which enables the high energy storage capacity to stabilize the interior temperatures of buildings and consequently ameliorate the thermal comfort sensation for indoor environment. The integrated PCMs in the building envelope change state from solid to liquid which results in reducing the wave fluctuation of building's interior temperature [9]. Current studies trend to sustainable buildings with development of new techniques of energy storage and of renewable energy sources. Integration of PCMs into building walls trend to make use of solar energy [10].

The Integration of the microencapsulated PCMs into buildings envelop attracted the attention of many researcher's which is presents a new technology in the building systems. An experimental and numerical work of Lachheb et al. [11] showed that the thermal storage capacity of the microencapsulated PCM in plaster wall is greatly enhanced. Zalba et al. [12] reported the advantages of the enthalpy method to treat the energy equation in relation with the PCM melting and solidification. They are reviewed some simulations and theories of heat transfer and phase change. In using a simulation in typical environment condition for one year, Pasupathy et al. [13] developed a model of incorporation of a PCM in a roof. They analyzed the effect of the variation of the environment condition on heat transfer coefficient along the surface of the roof. Khillarkar et al. [14] proposed two different configurations of tube geometries to study numerically the melting process of a phase change material. They found that the thermal stratification is obtained in the upper section of the cavity. Vyshak and Jilani [15] numerically studied the effect of different configurations rectangular, cylindrical and shell and tube contains the identical volume and surface area of heat exchange of latent heat thermal storage (LHTS). Their results showed that the effect of geometry is more important with an augment in the mass of the PCM and the geometry of the cylindrical shell containers which takes minimum time for equal quantity of energy storage.

In the present work, and in order to enhance the thermal behavior in building equipment, a numerical analyse of unsteady state heat transfer in three arrangements of cavity section is presented to study phase change process of PCM (*Phase Change Materials*). These arrangements are: square, cylindrical and elliptical cavities, which are tested for different thickness. Where, the present paper out to determinate the effect of the arrangement and PCM thickness of the cavity section on the thermal behavior during the melting/solidification process.

2. MODEL VALIDATION

The proposed numerical model was verified by comparing the results of simulation with the experimental results of literature [11]. In this section, we considered the enthalpy method to study the thermal problem of PCMs. The physical problem and the boundary and initials conditions are given below in fig.1. The initial temperature is supposed to be uniform (T_0). The dimensions of the wall are l=2 cm and w=25 cm in X-direction and Y-direction respectively. Otherwise, the wall is submit to variation temperature $T_p(t)=\theta t+T_0$ on the two vertical faces, the two horizontal faces are insulated $(\partial T/\partial y)=0$. Thus, the problem can be simplified as unidirectional heat transfer by conduction through the PCMs medium. The natural convection in the PCMs medium is discarded because of low dimensions of the wall.

The proposed mathematical model contains certain assumptions that are important considerations that have already been tested and do not have an influence on the creation and use of this model. It is assumed as: the PCM wall is homogeneous medium and isotropic, the heat transfer process in the PCM wall is dominated by conduction, the heat transfer is unidirectional and perpendicular to the PCM wall, the melting/solidification process in the PCM is assumed to be isothermal, the thermo-physical properties of PCM are different on the solid and liquid phases.

Given these assumptions, the enthalpy formulation for the conduction-controlled the phase change can be written as follows [11]:

$$\frac{\partial H}{\partial t} = \nabla \cdot \left(k \nabla T\right) \tag{1}$$

where k is the thermal conductivity, T is the temperature, and H(T) is the enthalpy.

As stated above, an alternative form Eq. (1) can be obtained by setting up the sensible and latent enthalpies explicitly [11]:

$$H = h + \rho f L \tag{2}$$

where (*f*) is the volume fraction of the liquid, ρ is the density, and (*L*) is the latent heat. The sensible enthalpy of the PCM can be given in terms of the temperature and the specific heat by the following relationship [11]:

$$h = \int_{Tm}^{T} \rho c dT \tag{3}$$

where T_m is the melting temperature.

In the case of an isothermal phase change, the liquid phase fraction (*f*) is defined as [11]:

$$f = \begin{cases} 1 & if \quad T > T_m \\ 0 & if \quad T < T_m \end{cases} \tag{4}$$

Note that-Eq. (1) can be handled via iteration steps to solve the temperature evolution equation due to the non-linear latent-heat source term existing in the energy equation (Eq. (5)). So, the general enthalpy formulations, taking into account both sensible and latent parts can be given by [11]:

$$\frac{\partial h}{\partial t} = \nabla \cdot \left(\alpha \nabla h\right) - \rho L \frac{\partial f}{\partial t} \tag{5}$$

The above equation (eq. 5) along with initial and boundary conditions and Eqs. (3)–(4) represents the mathematical model governing heat conduction and isothermal phase change. It is worth noting that such a formulation is suitable, since the liquid fraction is regarded as a source term. Since the Eq. (5) is non-linear, it can only be solved numerically.

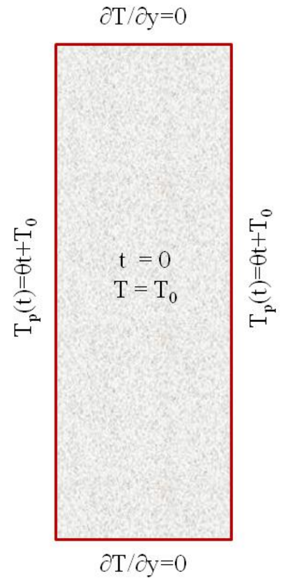


Figure 1. Boundary conditions of the PCMs wall

The solution of unsteady-state heat equation (5) to analyze PCMs wall by using an implicit finite volume method, where the CFD software is used to calculate the temperature and heat flux in PCMs medium. To obtain converged solution, the wall is devised in 100 nodes and the time step Δt=1s, the thermophysical parameters are given in table 1.

Table 1. Thermophysical properties of materials [11]

Thermophysical properties	Value (unit)
Thermal conductivity solid	0.266 ($Wm^{-1}K^{-1}$)
Thermal conductivity liquid	0.236 ($Wm^{-1}K^{-1}$)
Heat capacity solid	915 ($Jkg^{-1}K^{-1}$)
Heat capacity liquid	725 ($Jkg^{-1}K^{-1}$)
Latent heat	11265 (Jkg^{-1})
density	1213 (kgm^{-3})

These figures show a good agreement between the results of simulation and experimental data. The comparison was carried when the PCMs in the solid phase (T_0 = 17 °C, T_{end} =

23 ºC) storage of energy by sensible heat, thus when the PCMs in the liquid phase (T_0 = 30 ºC, T_{end} = 38 ºC) storage of energy by latent heat. The choice of these values depended on the melting point T_m. The profiles of temperature and the heat flow in the two phases were compared with the experimental data obtained by [11]. It is significant to note that the heat flow to t=0s (the initial state) is equal to Q = 0 (w/m^2). Thus, we impose a variation in temperature on two vertical faces by the equation $T_p(t)=\theta t+T_0$ which induces a thermal evolution of the energy storage system to make a balance state more stable. Confrontation between the results of this work and the results of [11] are represented by the following curves which interpret the profiles of temperature and the heat flow.

Figure (2) presents the variation of imposed temperature and the heat flow bring to the composite materials (PCM + plaster) during 4000 S. We can observe that the wall takes its temperature of balance after a time of t=2750 S. However, the choice of the values of temperature (T_0=17 ºC, T_{end}=23 ºC) is imposed to study the thermal behavior of the composite materials (PCM + plaster) following the storage of heat in the solid state. Consequently, the wall stores a significant quantity of heat in the solid phase; it is calculated by the equation (6).

$$Q = \frac{1}{\rho e}\int_{t_{init}}^{t_{end}} \Delta\varphi dt \qquad (6)$$

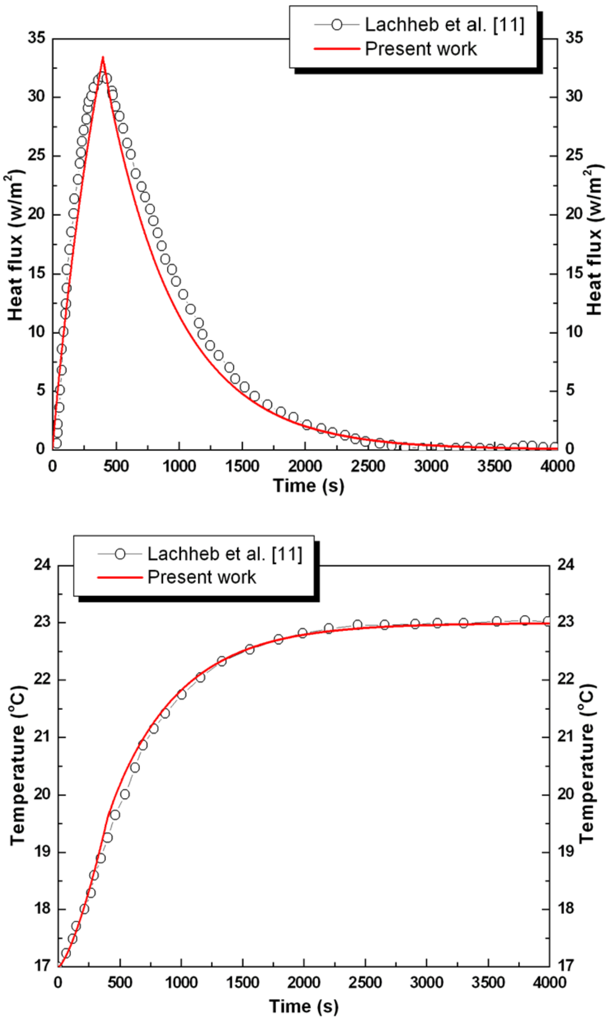


Figure 2. Variation in temperature and heat flux, solid phase (17ºC – 23ºC)

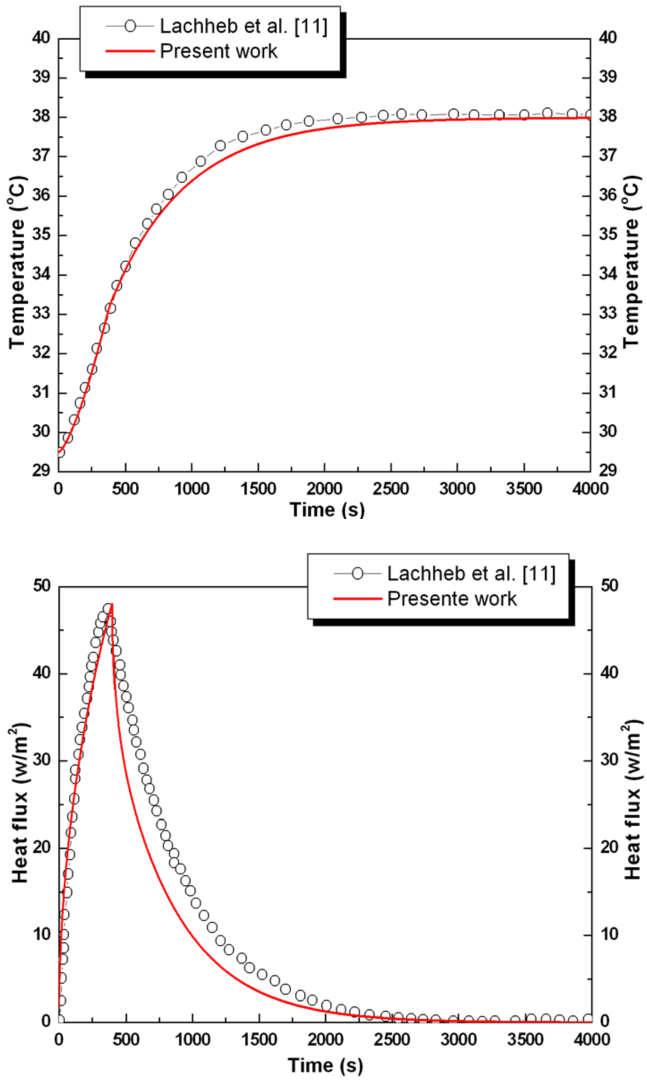


Figure 3. Variation in temperature and heat flux, liquid phase (30 ºC – 38 ºC)

The variation in the temperature and the heat flow as function of time shown in figure (3) are calculated at the ambient temperature higher than the melting point (T_0=30 ºC, T_{end}=38 ºC). However, we can observe as the composite materials (PCM + plaster) reached its temperature of balance after a time of t=2500s. Generally, the variation in temperature and evaluated heat flow numerically and the in experiments are similar.

3. THERMAL CHARACTERISTICS OF MCP IN THE SINUSOIDAL MODE

The figures (4) show the results obtained for three days of the period studied by considering the conditions of temperature of summer in French [11]. By analyzing the variation in the temperature and heat flux as function of time, we notice that the latter fluctuates between the maximum and minimal values in way which approaches with the periodic form.

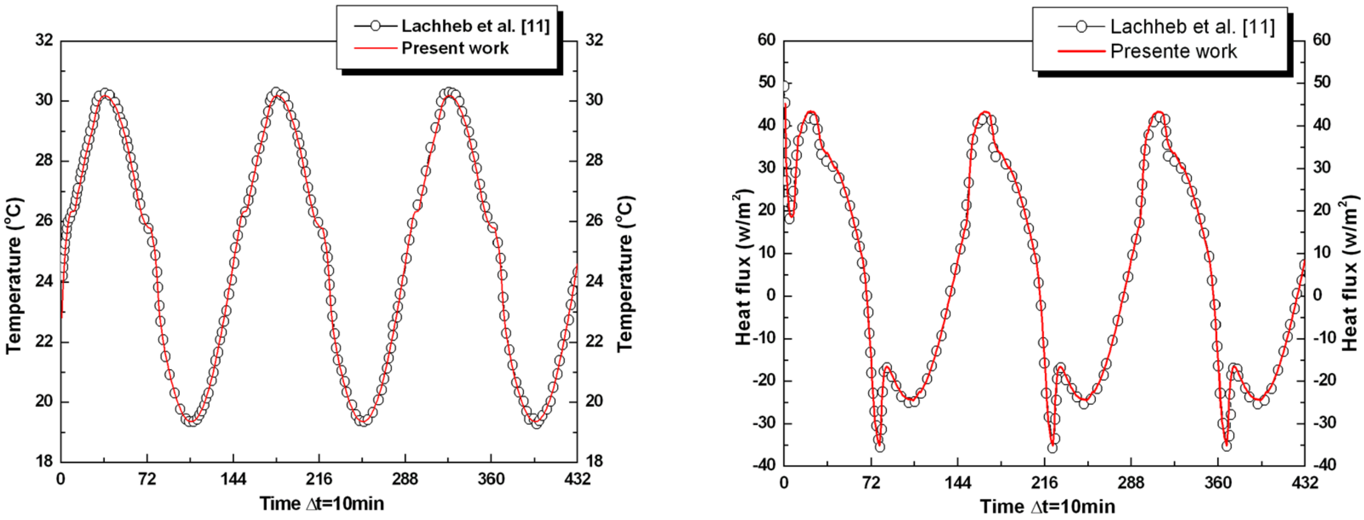


Figure 4. Variation in the temperature and heat flux on external surface of the wall

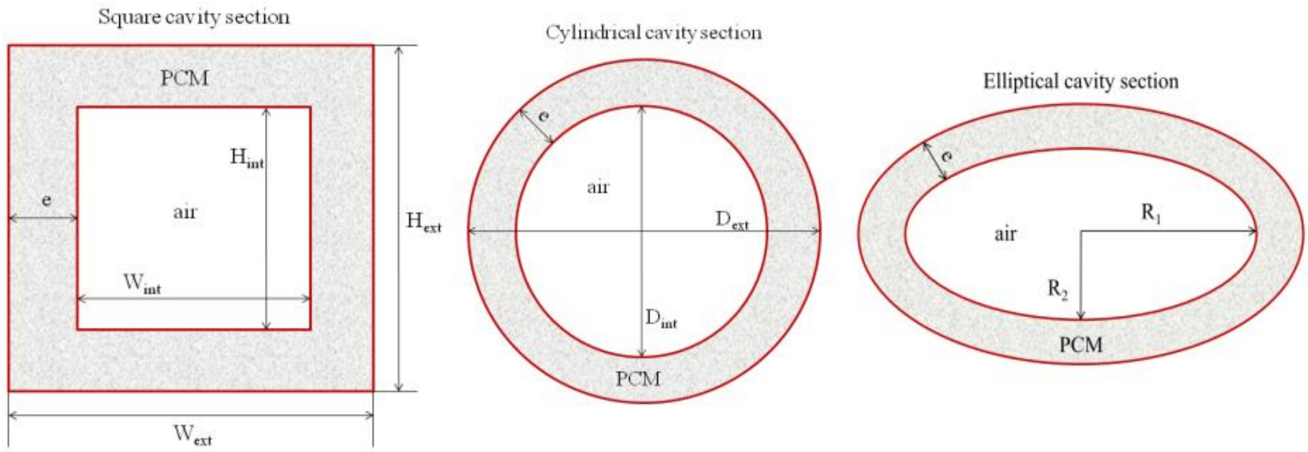


Figure 5. Analyzed Configurations; (a) square cavity section, (b) cylindrical cavity section and (c) elliptical cavity section

In order to realize this research, a three configurations presented in fig.5, a square cavity section with fixed internal dimension (20x20 mm^2), cylindrical cavity section with fixed internal dimension (D_{int}=20 mm) and elliptical cavity section with fixed internal dimension (R_1=10 mm, R_2=5 mm). The outer surface of the three configurations is exposed to sinusoidal outdoor temperature variation. The focus of this section is to evaluate the effect of the configuration of the cavity section in variation temperature.

$$T_{a,out} = 25 + 7\sin(\omega t) \tag{7}$$

where; ω is the pulsation $\omega = 2\pi/t$, the time τ =1440 min, the initial conditions are T(x,0)=T_0=20 °C.

The boundary condition at the external surface describted by:

$$-k_a \frac{\partial T}{\partial x} = h_{out}\left(T_a - T_{w,out}\right) \tag{8}$$

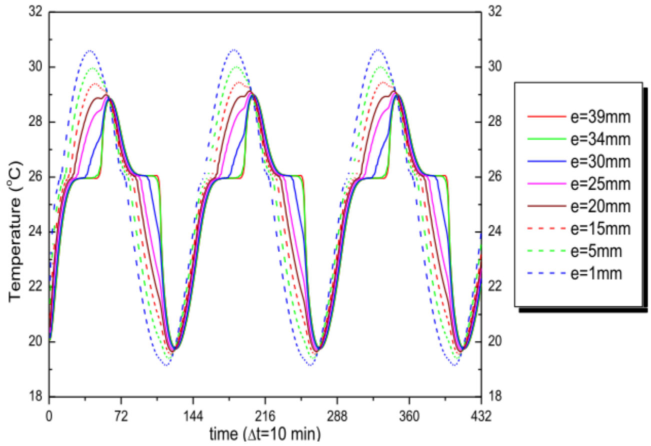
where; h_{out}= 18.6 W.m^{-2}.K^{-1} presents the outside heat transfer coefficient.

4. RESULTS AND DISCUSSION

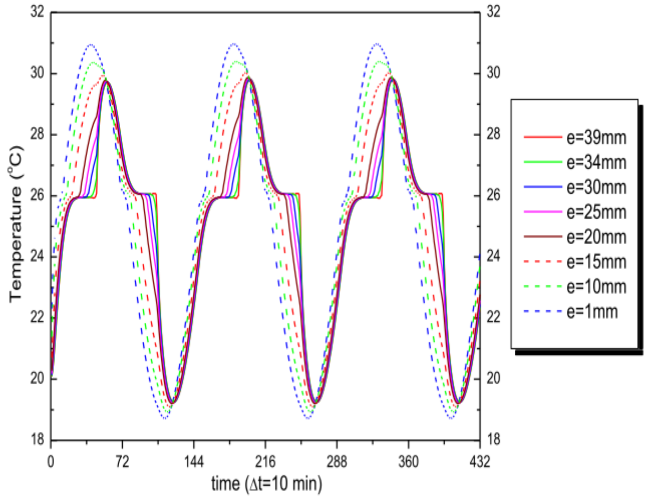
Figure (6-a) shows the effect of PCM thickness on the variation of temperature in the square cavity section. We can observe a variation of temperature between (e=1 mm and e=39 mm) is about 2°C, the maximum amortization time of the temperature in this zone is around Δt=135mn and the temperature stabilized near the melting temperature T_m=26 °C. On the other hand, the increase of thickness of PCM has an important influence on the PCM thermal energy storage. In figure (6-b) it is possible to observe a gradient of temperature in the zone between (e=1 mm and e=39 mm) is about 1.6°C and the maximum amortization time is around Δt=194 mn.

In the same manner, figure (6-c) shows the evolution of temperature as function of time with different thicknesses. In this figure, we can observe a decrease near the melting temperature in each cycle. The time increased with the depth of PCM to allow the decrease the heat transfer inside the cylindrical cavity section, the amortization time between the external and internal surfaces is about Δt=362 mn. The stratification of temperature in this configuration is remarkable and the gradient of temperature is around 1.9 °C.

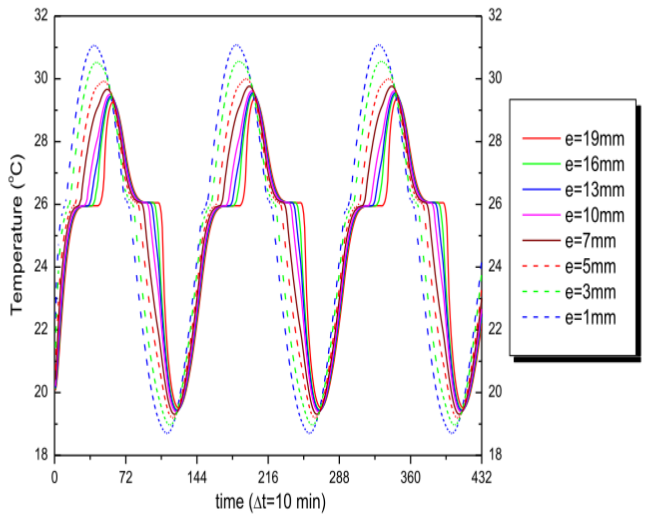
Figure (7-a) shows the calculated temperature in the centre of the cavity for different thicknesses of PCM. While the temperatures superior to T_m=26 °C presents the absorbed heat flux during the melting phase but for temperature inferior to T_m=26 °C presents the release of the stored energy. The complete melting process of the square cavity section with 40mm of thickness is complete after t=500 mn, this time is caused by the high thermal storage of PCM thickness.



(a)

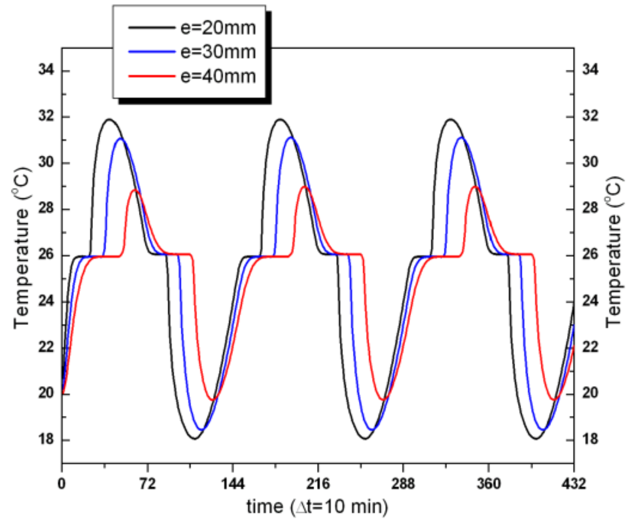


(b)

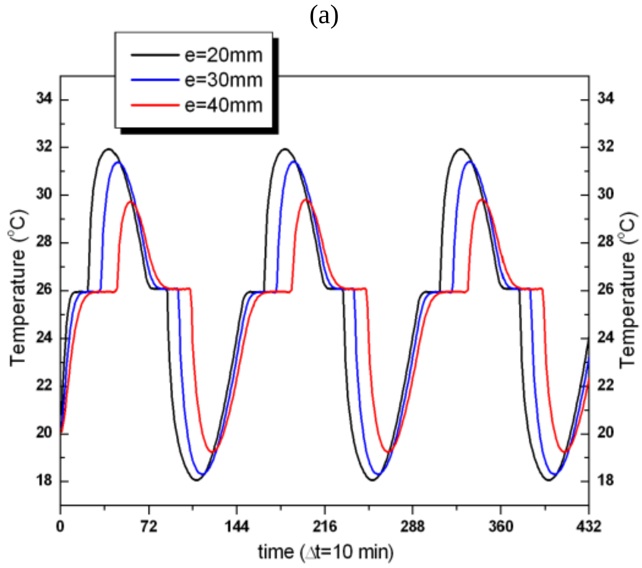


(c)

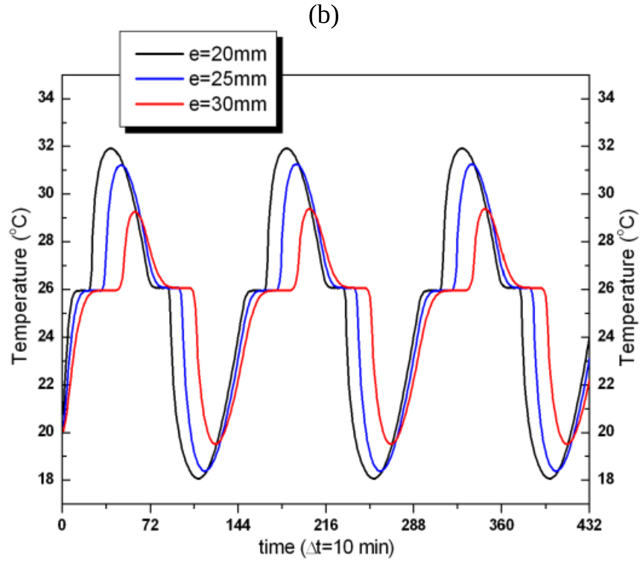
Figure 6. Evolution of temperature with different thicknesses as function of time in: (a) square cavity section, (b) cylindrical cavity section, (c) elliptical cavity section



(a)



(b)



(c)

Figure 7. Temperature variation in the centre of the air cavity with different PCM thickness in: (a) square cavity section, (b) cylindrical cavity section, (c) elliptical cavity section

In the same manner, figure (7-b) presents the temperature at the centre of the cylindrical section cavity; the present results compared to external temperature shows a decrease of the air cavity temperature fluctuations of around 2 ^{o}C on the case of cylindrical cavity section. It is possible to identify the effect of thermal energy storage on the air temperature, the melting/solidification of the PCM is more important to stabilize the temperature in the range of melting temperature. Figure (7-c) shows, that the air temperature at the centre of elliptical section cavity for 10mm of PCM thickness can decrease the air temperature about 3 ºC in heating period and increase the air temperature about 2 ºC.

5. CONCLUSION

In this paper, a comparative study is carried out to evaluate the effect of the configuration of cavity section and the PCM thickness of the containers. The melting/solidification of PCM is more effective, because of its influence on the temperature of cavity confined air, about 5 ºC of difference was observed. Therefore, the different configurations showed that the elliptical cavity section with 10mm of PCM thickness can maintain the air temperature in same values in the case of square and cylindrical cavity section with 20mm of PCM thickness. The results showed the potential of the melting/solidification process of PCM in the air temperature of the different configurations. Application of PCM containers in the building sector can maintain the interior air temperature in the range of melting temperature and decrease the energy consumption.

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NOMENCLATURE

T	temperature (K)
T_0	initial temperature (K)
T_p	temperature imposed on two faces (K)
T_m	melting temperature (K)
t	time (s)
D_{int}	Internal diameter (mm)
e	thickness (mm)
C_p	specific heat ($J.kg^{-1}.K^{-1}$)
H	total enthalpy ($J.m^{-3}$)
f	liquid fraction
L	latent heat of fusion ($J.kg^{-1}$)
h	specific enthalpy ($J.m^{-3}$)
m	mass (kg)
k	thermal conductivity ($W.m^{-1}.K^{-1}$)
Q	total stored energy (J)
ρ	density ($kg.m^{-3}$)
α	Thermal diffusivity ($m^2.s^{-1}$)
θ	heating/cooling rate ($^oC.min^{-1}$)
φ	heat flux ($W.m^{-2}$)
τ	period (min)