Numerical study of the thermal behavior of a wall containing phase change material (PCM) in a hot and dry climate

ABSTRACT

Current buildings in Burkina Faso, particularly in the Sahelian zone, built with local materials are energy-intensive and sources of discomfort for the occupants. However, the role of housing is to provide man with shelter which protects him from external climatic conditions and offers him thermal comfort.
In this work, we present a numerical study of the thermal behavior of a wall containing a phase change material (PCM) in the Sahelian zone. The MCP used in this study is RT27 paraffin with a melting temperature of 27°C and a latent heat of fusion of 179kJ/kg. The equations obtained were adimensionalized and discredited by the finite element method and solved using COMSOL Multiphysics software version 5.3. To this end, we were interested on the one hand in the study of the evolution of the flow of heat and the temperature at the level of the external and internal walls of the wall. On the other hand, we studied the effect of the location of a layer of PCM mortar, simple plaster or cement plaster on the temperature of the internal wall of the wall. The results show the magnitude of heat flux and temperature is greatly reduced by the incorporation of PCM into the wall.

Keywords:Numerical study, phase change materials, RT27 Paraffin, COMSOL, thermal.

1. INTRODUCTION

In Burkina Faso, the walls of buildings are constructed with hollow breeze blocks. These walls are confronted with thermal disturbances during periods of heat. These are caused by strong heat received by the external faces of the walls. This generates a significant consumption of energy within the building for internal cooling. This results in high charges.
According to a study carried out by the Ministry of Energy of Burkina Faso, the amount of energy consumed per year in buildings is 470.807MWh with a consumption index of 232kWh/m2/year [1]. To reduce this energy consumption in a context marked by global warming and a scarcity of energy resources of fossil origin, it is necessary to consider new thermal insulation materials in building structures in order to reduce the heat in buildings. To this end, some studies have focused on materials that better regulate heat transfer in buildings. Among these materials, we have the phase change materials commonly called PCM.
The incorporation of PCMs, in the different construction elements, is done by different methods which are the direct incorporation of the PCM, the impregnation of the construction material, the incorporation of capsules filled with PCM in the construction elements, etc. [2].Their uses for air conditioning and heating in buildings show that the temperature peaks in a room equipped with PCMs can be reduced by 3 to 4°C, thus reducing the energy consumption linked to air conditioning by 30% [2].
Numerous numerical and experimental studies have been carried out in recent years to assess the potential for using the integration of a PCM in bricks, walls and/or building envelopes and to increase its thermal inertia to improve their energy performance [3-9].
The objective of this work is to study the evolution of the heat flux and the temperature in a wall containing PCM when it is subjected to external and internal convective stresses.

2. DESCRIPTION OF THE PROBLEM

Figure 1 shows a rectangular wall with a height 3m and a thickness e = 0.15m. The wall is made of hollow cement blocks whose empty cavities are filled with PCM. The outer surface of the wall is subject to convective flow.

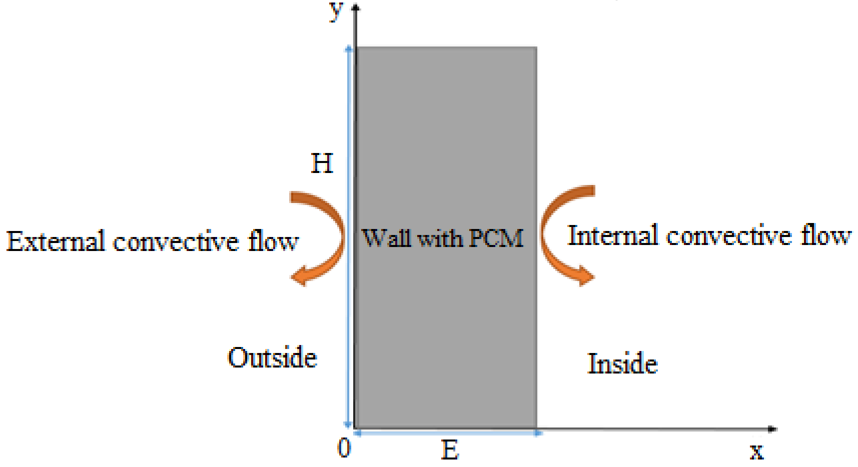

Fig. 1. Physical model of PCM

In this study, we chose paraffin as thermal energy storage materials because of its large storage capacity, the absence of segregation and undercooling phenomena as well as their chemical and non-corrosive stability [10-12].The paraffin chosen is RT27, the phase change temperature of which is 27° C. and its latent heat of fusion 179 kJ/kg. The thermophysical characteristics of the PCM used are presented in the table.

Table 1. Thermo-physical properties of the materials used for the study [13] [14]

	T_f (K)	$L_f\,(J/kg)$	$k\,(W/m/K)$	$\rho(kg/m^3)$	$Cp\,(J/kg/K)$
Paraffin RT27	300.15	179000	0.24(solid) 0.15(liquid)	870(solid) 760(liquid)	2400(solid) 1800(liquid)
Wall			0.4	1200	880

3. MATHEMATICAL MODEL

3.1. Simplification assumptions

The simplifying assumptions of the problem are as follows:

- heat transfer is two-dimensional (2D) and transient;
- the thermo-physical properties (thermal conductivity, density and specific heat) of the wall are constant;
- the thermo-physical properties of PCM are constant and homogeneous but may be different in the liquid and solid phases;
- the effect of the natural convection of the liquid PCM is not taken into account because it is insignificant when the temperature difference between the liquid and solid phase is low;
- convection and radiation within the materials are negligible;
- the materials used are homogeneous and isotropic.

3.2. Mathematical equations

Considering the hypotheses mentioned, the equations that describe the phenomenon are written as follows:

$$\rho Cp \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad \textbf{(1)}$$

Thermo-physical properties ρ , Cp et k respectively, density, specific heat and thermal conductivity depend on the materials constituting the domain, namely the wall and the PCM.

In order to integrate the liquid and solid phase properties as well as the latent heat of fusion, an apparent property is used for phase change materials. The expressions describing the thermo-physical properties of PCM are:

$$\rho_{MCP} = \theta.\rho_s + (1-\theta)\rho_l \quad \textbf{(2)}$$

$$k_{MCP} = \theta.k_s + (1-\theta)k_l$$

$$Cp_{MCP} = \frac{1}{\rho_{MCP}}\left(\theta.\rho_s Cp_s + (1-\theta)\rho_l Cp_l\right) + L_f \frac{\partial \alpha_m}{\partial T}$$ **(3)**

α_m represents the mass fraction of the solid phase of the PCM. It is given by the following relation:

$$\alpha_m = \frac{1}{2}\frac{(1-\theta)\rho_l - \theta\rho_s}{\theta\rho_s + (1-\theta)\rho_l}$$ **(4)**

With $\theta = \begin{cases} 1 & si \quad T < T_s \\ \dfrac{T-T_l}{T_s-T_l} & si \quad T_s \le T \le T_l \\ 0 & si \quad T > T_l \end{cases}$ represents the volume fraction of the solid phase of the PCM, T_s and T_l are respectively the temperatures of the PCM in the solid and liquid state.

3.3. Initial and boundary conditions

- **Initial conditions :**

At time t=0s, the different layers of the wall are at the same temperature. The initial condition translates to: $0 \le x \le E$ and $0 \le y \le H$, we have : $T(x, y, 0) = T_{amb} < T_f$ **(5)**

- **Boundary conditions :**

The boundary conditions for the computational domain at $t \ne 0$ are as follows:

External face of the wall :

At time $t > 0$we impose on the external face, a convective heat flux:

For $x = 0$ and $0 \le y \le H$, we have : $-\lambda \left.\dfrac{\partial T}{\partial y}\right)_{0,y} = h_{conv,ext}\left(T_{ext}(t) - T_{PM,ext}\right)$ **(6)**

with : $T_{ext}(t) = A + B.\cos(\omega.\mathrm{t}) + \mathrm{C}.\sin(\omega.\mathrm{t})$ **(7)**

Internal face of the wall :

At time $t > 0$we impose on the internal face, a convective heat flux:

For $x = e$ and $0 \le y \le H$, we have : $-\lambda \left.\dfrac{\partial T}{\partial y}\right)_{e,y} = h_{conv,\mathrm{int}}\left(T_{int} - T_{\mathrm{PM,int}}\right)$ **(8)**

- **Interface wall/PCM and PCM/Wall**

At the wall/PCM interface, we assume that there is a continuity of heat flow.

Interface wall/ MCP :

$$k_{mcp}\frac{\partial T_{mcp}}{\partial n} = -k_m \frac{\partial T_m}{\partial n}$$ **(9)**

Interface PCM/wall :

$$k_m \frac{\partial T_m}{\partial n} = -k_{mcp}\frac{\partial T_{mcp}}{\partial n}$$ **(10)**

With « n » the normal to the surface of the cavity filled by PCM.

- **Horizontal face of the wall:**

The boundary conditions for the horizontal walls are formulated as follows:

For $y = 0$; $0 \le x \le e$, we have : $\left.\dfrac{\partial T}{\partial y}\right)_{x,0} = 0$ **(11)**

For $y = H$; $0 \le x \le e$, we have : $\left.\dfrac{\partial T}{\partial y}\right)_{x,H} = 0$ **(12)**

The numerical simulation was carried out by the finite element method on COMSOL Multiphysics software version 5.3. The simulation duration is 24h with a constant time step of 0.1h (i.e. 6 minutes). The geometries of the wall, the physical

properties of the materials used as well as the initial and boundary conditions were defined in the software. An extra fine quadratic mesh was adopted with 4788 elements.
This allowed us to obtain a convergence criterion of the order of 1.2x10^{-4}.

4. RESULTSAND DISCUSSION

In this part, we will be interested on the one hand in the study of the evolution of the flow of heat and the temperature of the external and internal walls of the wall. On the other hand we will study the effect of the location of a layer of PCM mortar, simple plaster or cement plaster on the temperature of the internal wall of the wall. During the simulation, we imposed outside and inside a heat flux which varies according to time. We used constant values of the external and internal convective heat exchange coefficients. These values are respectively 16.7W/m^2/K and 9W/m^2/K [14].
The evolution of the temperature is controlled by waves placed mainly on the external and internal faces of the wall.

4.1. Evolution of the heat flow at the level of the internal face of the wall

Figure 2 presents the evolution of the heat flux as a function of time at the level of the internal wall.

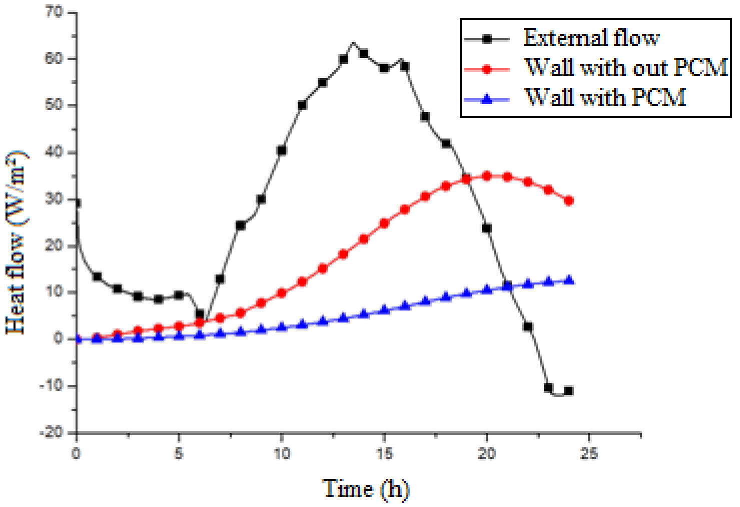

Fig. 2. Evolution of the heat flow in the wall over time

The curve in figure 2 shows us the variation of the heat flux in the wall and in the atmosphere as a function of time. We observe an increase in the heat flow from the first moments then a decrease from 3 p.m. We note that the heat flow received at the level of the interior surface of the wall containing the PCM is lower than that received by the wall without PCM with a maximum value respectively of 12.537W/m^2 and 35.055W/m^2 with a difference of 22.518 W/m^2. This gap means that the wall containing the PCM opposes the passage of a large part of the heat received at the level of the outer surface from penetrating inwards.
This shows that the use of PCM in the wall contributes to reducing the heat flow while providing thermal resistance to external stresses due to its high latent heat of fusion (179kJ/kg) and its low thermal conductivity (see table 1).
We also observe that the outgoing heat flux at the level of the interior surface of the wall at the end of the day is higher than that entering at the level of the exterior surface. This shows that the wall has stored a large part of the heat received during the day.
Also, we observe in Figure 2 that the heat flux received at the level of the outer surface decreases from 3 p.m. and thus reaches limit values yielded in the external environment, thus reversing the direction of propagation of the flux.
The following table 2 shows the average flow entering and leaving the wall

Table 2. Average flow entering and leaving the wall

	Average flow entering $\phi_{ent}\left(W/m^2\right)$	Average flow leaving $\phi_{sort}\left(W/m^2\right)$	Difference $\phi = \phi_{ent} - \phi_{sort}$
Mur sans MCP	27.58	17	10.58
Mur avec MCP	27.58	5	22.58

We observe that the average heat flux leaving the wall containing PCM is lower than that leaving the wall without PCM with a difference of 10W/m^2. Similarly, the average heat flux stored in the wall containing PCM is greater than that without PCM with a difference of 12W/m^2. This shows that the PCM stores a large part of the heat received at the external surface of the wall during its melting as latent heat.

4.2. Evolution of the temperature at the level of the internal face of the wall

Figure 3 presents the evolution of the temperature as a function of time at the level of the internal wall.

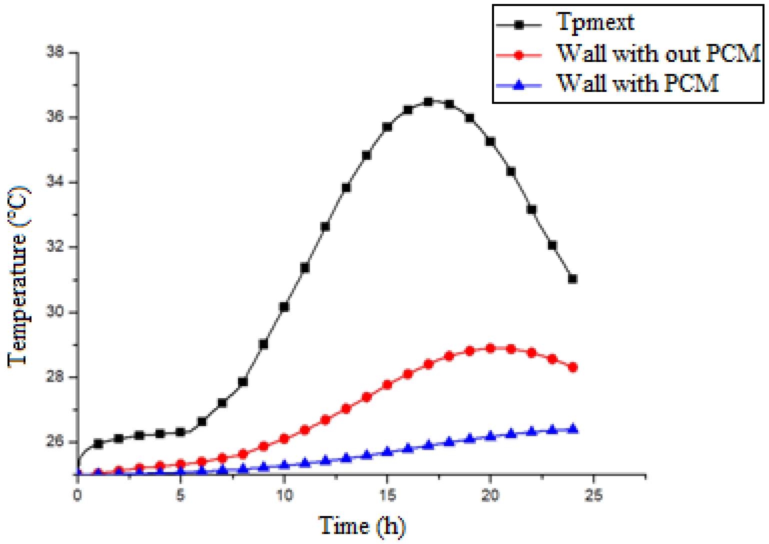

Fig. 3. Evolution of the temperature at the level of the internal face over time

The curve in Figure 3 shows us the temperature variation at the level of the external and internal wall of the wall without PCM and with PCM as a function of time. We observe that the maximum amplitude of the temperature at the level of the external wall of the wall with or without PCM is 36.48°C while that of the internal wall is respectively 26.39°C and 29°C for a wall with PCM and for a wall without PCM. The temperature difference between the internal wall of a wall containing PCM and/or without PCM and the external wall of the wall is respectively 10.09°C and 7.48°C. We observe in Figure 3 that the amplitude of the temperature oscillations of the inner face of the wall containing the PCM is greatly reduced compared to that of the wall without PCM with a difference of 3.39°C. Hese observations show that the PCM contributes to keeping the wall temperature low and thus limits the heat transmitted to the interior side.

This is due to the large amount of heat absorbed during the melting of PCM in the form of latent heat. This fusion of the PCM helps to keep the temperature of the material constant and thus limits the heat transmitted to the interior side. It can also be explained by the effect of the thermal conductivity of the PCM which is low compared to that of the hollow cement block; which makes it more insulating by acting to slow down the phase change process, but this effect is weak compared to the effect of the latent heat of fusion.

4.3. Study of the effect of the location of the PCM

We will then analyze the behavior of the wall according to the location of the PCM for a thickness of 2.5 cm. Figure 4 shows the effect of the location of the PCM on the evolution of temperature over time.

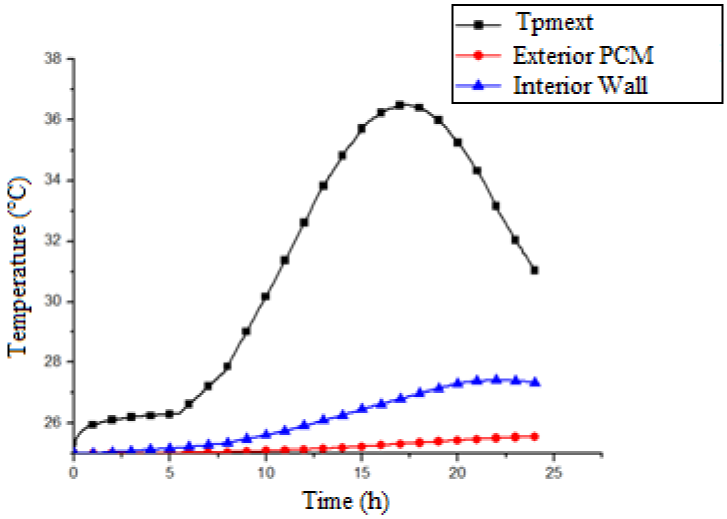

Fig. 4. Evolution of the temperature of the internal wall of the wall over time

The curve in Figure 4 shows us the variation in temperature at the level of the external and internal wall of the wall as a function of time when the MCP is placed either outside or inside the wall. We note that the maximum temperature reached at the level of the external wall of the wall is 36.48°C. Also in the figure the results indicate that for a wall whose MCP is placed outside the maximum temperature of the internal wall reached is 25.563°C while for a wall whose MCP is placed inside the maximum temperature is 27.406°C (difference of 1.843°C). It can be seen that the amplitude of the temperature of the internal wall of the wall of which the MCP is placed outside is small compared to that of which the MCP is placed inside. This is justified by the fact that the PCM placed outside absorbs a lot of heat coming from the external environment, which makes it possible to reduce the flow of heat in the interior space of the wall.
This result is in agreement with that found by Haghshenaskashani et al who showed that for good insulation, the PCM must be placed at the level of the face of the wall exposed to the external ambient environment [14]

4.4. Study of the effect of the location of a mortar

In this part, we analyze the results obtained for a wall composed of a 0.025m layer of plaster mortar, simple plaster and PCM. The thermophysical properties of the plaster and the render are presented in Table 3 below.

Table 3. thermophysical properties of plaster and coating [15]

	$\rho\left(kg/m^3\right)$	$k\left(W/m/K\right)$	$Cp\left(J/kg/K\right)$
Plaster	1450	0.45	880
Coating	1700	1.15	1000

Figures 5 and 6 show the evolution of temperature in a wall made of plaster mortar, simple render and MCP as a function of time.

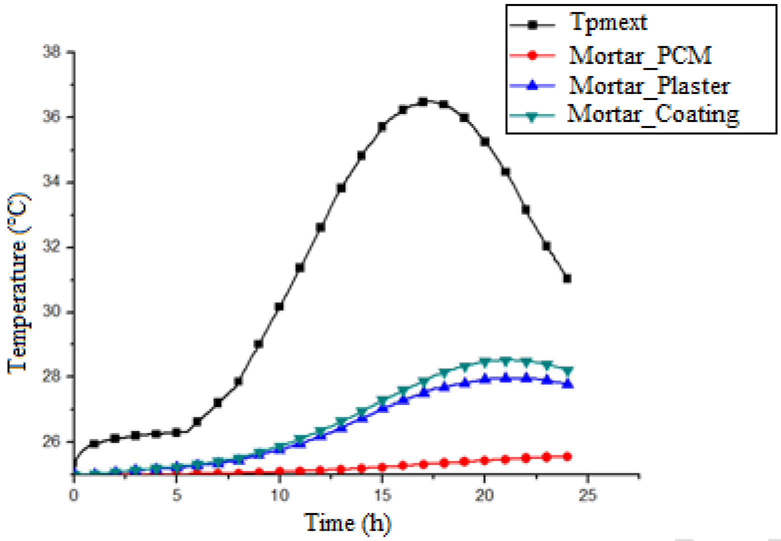

Fig. 5. Evolution of the temperature at the level of the internal face over time for a layer of mortar placed outside

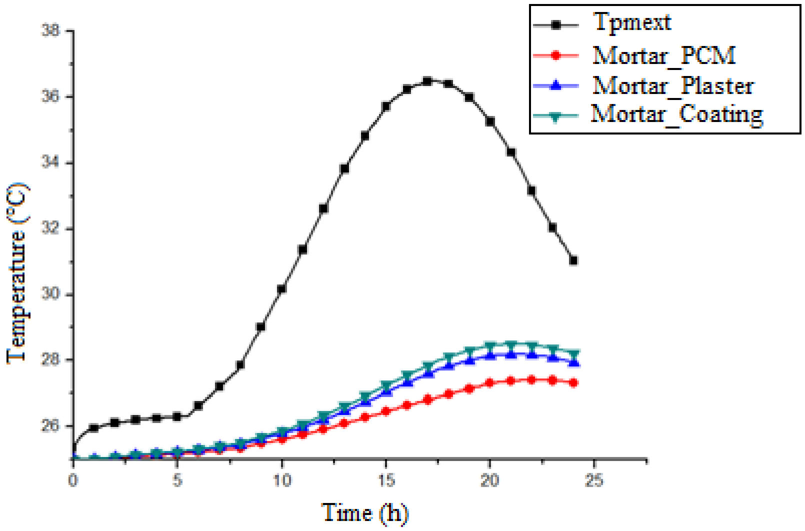

Fig.6. Evolution of the temperature at the level of the internal face over time for a layer of mortar placed inside

The curves in Figures 5 and 6 show us the variation in temperature at the level of the external and internal wall of the wall as a function of time when a layer of cement mortar, plaster and or PCM is placed outside (figure 5) or either inside (figure 6) the wall. We also observe that the maximum amplitude of the temperature of the internal wall of the wall is greatly reduced for a wall containing PCM compared to that composed of cement rendering or simple plaster. The maximum temperatures observed in Figure 5 are respectively 28.52°C, 27.963°C and 25.563°C for a wall whose mortar layer is plaster, plaster and PCM. Also the level of temperature reached at the level of the outer wall of 36.48°C with a temperature difference of 7.96°C for a wall whose layer of mortar is plaster; 8.517°C for a wall with a simple plaster mortar layer, while that of an PCM mortar layer is 10.917°C.

In Figure 6, the maximum temperatures observed are 28.187°C for a wall whose layer is plaster; 28.494°C for a cement mortar wall and that of a PCM mortar wall is 27.406°C. Compared to the temperature of the outer wall, we find a respective temperature difference of 8.293°C; 7.986°C and 9.074°C.

The temperature difference between a layer of mortar placed outside and inside is 0.224°C respectively; 0.026°C and 1.843°C. The temperature differences observed in Figures 5 and 6 are explained by the low thermal conductivity value of the PCM compared to that of the render and the plaster (see Tables 1 and 3). This makes it more insulating by acting to slow down the phase change process.

5. CONCLUSION

In this work, we have numerically simulated the thermal behavior of a wall containing a phase change material (PCM) located in Ouagadougou. The phase change material used in this study is paraffin RT27. The equations were discredited by the finite element method and the numerical simulation of the thermal behavior of the wall was carried out on the software COMSOL Multiphysics version 5.3. From the results obtained, we draw the following conclusions:

- the maximum amplitude of the heat flow and of the temperature are greatly reduced for a wall containing PCM compared to that of a wall without PCM with a heat flow difference of 22.518W/m2 and a temperature difference of 3.39°C.
- the study of the location of a mortar layer on the wall shows that the maximum temperature amplitude is reduced for a wall whose mortar layer is PCM but by comparison this amplitude is lower when the mortar layer is PCM mortar is placed outside the wall with a temperature difference of 1.843°C.

The results obtained show that the use of PCM makes it possible to reduce temperature peaks and increase the thermal inertia of the wall

In perspective, we will consider studying the influence of the type of PCM on the thermal performance of a composite wall in the Sahelian zone.

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