Numerical study of the efficiency of integrating phase change material into a clay-straw wall in the Drâa-Tafilalet region (Errachidia Province)

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Abstract. The objective of this study is to evaluate the thermal performance of clay-straw walls of buildings integrating phase change materials (PCM). The influence of integrating different types of PCM in the envelope has been studied numerically in several studies. The optimal wall thickness with PCM integrated suitable for the climatic conditions of Errachidia has been studied. The heat balance equations for the different wall configurations are formulated and solved numerically under the same climatic conditions. The results obtained show that the integration of PCM in the clay-straw wall instead of the cement wall increases the heat flux density as a function of time by up to 80 % based on the thermal properties of the PCM and the environmental conditions of the study.

1 Introduction

The use of renewable energies and the reduction of conventional energy consumption as a way of trying to improve environmental problems such as global climate change has become the main concern of the scientific engineering research that is currently being developed [1]. Countries need to orientate to renewable energy consumption in energy policies[2], [3]. In the same context, the use of phase change materials (PCMs) for thermal energy storage strategies in buildings can meet potential thermal comfort requirements when they are properly selected. A summary of the PCMs used and their respective properties are also presented[4]. Various researches have been carried out to study phase change problems and the effect of the heating and cooling conditions. Kaba et al. [5] developed an efficient numerical phase change model for modeling both the isothermal and non-isothermal phase change problems. El Idi et al.[6] studied numerically the effect of

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cyclical heating and cooling conditions on phase change kinetics of paraffin-embedded in a metal foam. Meng et al.[7] proposed a new partial copper foam filler to improve the thermal performance of latent thermal storage units, which not only responded to the background of thermal utilization of solar energy but also occupied the low PCM position, which was in favor of ensuring thermal storage density. Systems studied are shown to be effective in reducing indoor temperature fluctuations and energy demand during cold seasons, as well as the ability to trigger load reduction [8]. Al-Absi et al.[9] investigated the potential of passive application of PCMs for the indoor environment of buildings in the warm-humid climate of Malaysia. In addition, the capacity of PCMs to reduce the maximum indoor air temperature of buildings naturally conditioned in a warm-humid climate region by storing night-time coolness is studied. There are different ways of integrating PCMs in buildings. Many previous experimental works show the integration of PCMs into wall systems via gypsum plasterboard. [10] [11], wall panels [12] [13], external bricks [14], [15] or in the interior of the insulation cavity [16] [17]. Other present PCM integration in floors [18]. Also there are some experimental and simulation researches on the optical and thermal performance of glazing units containing PCM [19] etc. We investigated experimentally [20] the integration of PCM (paraffin 21.7) in a clay-straw wall in order to reduce the energy consumption of buildings in the Drâa-Tafilalet Region (Errachidia Province), Morocco. The objective of this paper is to evaluate the effectiveness of using PCM in the building envelope in the Drâa-Tafilalet region (Province Errachidia). An evaluation of the effect of incorporating 4 different PCMs into a clay-straw wall in terms of reducing cooling needs is presented. And finally, a comparative study between clay-straw walls and cement walls is investigated.

2 Materials and methods

2.1 The problem statement

The wall studied in this paper is a clay-straw wall incorporating a PCM. The geometry of these walls is shown in Fig. 1. Four different PCMs are used, which differ mainly in their median melting temperature T_m and composition as shown in Table 1.

Fig. 1. The different wall configurations: (a) Wall without PCM, (b) Wall with 0.5 cm of PCM, (c) Wall with 1 cm of PCM, (d) Wall with 2 cm of PCM.

Table 1. Thermophysical properties of the clay-straw and PCMs [21][22], [23][24][25]

Material	median melting temperature (°C)	Thermal conductivity (W/m.K)		Density (kg/m³)		specific heat capacity (J/kg·K)		latent heat of fusion Lf (KJ/Kg)
		Solid	Liquid	Solid	Liquid	Solid	Liquid	
Clay-straw	----	0.28	---	1537	---	786	---	---
Cement	----	1.153	---	1700	---	1000	---	---
PCM 24 (Paraffin)	24	0.21	0.21	900	760	2100	2100	144
PCM 27	27	0.577	0.813	1710	1530	1751	2225	172.42
PCM32 (Capric-Acid)	32	0.149	0.149	1004	886	2096	2088	152
PCM 37 (n-Eicosane)	37	0.15	0.15	778	856	2010	2040	241

2.2 Numerical model

2.2.1 Hypotheses

In order to evaluate the variations in temperatures and heat flows in clay-straw brick incorporating a PCM and in order to write the equations governing the physical problem to be solved, it is necessary to make a number of assumptions:

- The thermophysical properties of PCM are constant but may be different in the liquid and solid phases (conductivity, specific heat, and density).
- The material is assumed pure and the change of state takes place at a constant temperature T_m (melting temperature).
- The problem is two-dimensional and transitory.
- Constant thermo-physical properties of the brick.
- PCM is homogeneous and isotropic.
- No humidity inside the brick, and therefore no heat source due to evaporation.
- Perfect contact between the PCM and the surfaces of the clay-straw layer
- Negligible convection in the liquid phase of the PCM.
- Narrow phase change temperature range (1°C).
- PCM expansion is neglected and phase change is isothermal.
- No radiative exchange with the soil.

2.2.2 Boundary and initial conditions

The external wall surface receives solar radiation, which depends on the orientation (south) of the wall and time, and exchanges heat by convection with the outside air. The boundary condition at the external wall surface is as follow:

$$\phi_e = h_e(T_e - T_w(x = 0, y, t)) + \alpha q_s(t) \quad \forall y \in [0, H] \quad (1)$$

where the wall solar absorption coefficient is assumed to be $\alpha = 0.6$ [23] and the outside convective heat transfer coefficient is assumed to be $h_e = 25 \text{ W/(m}^2 \cdot \text{K)}$ [26].

All these boundary conditions are explicitly shown in Fig. 1

A convective boundary condition is applied to the internal surface of the wall under consideration, supposing that the inside temperature is $T_i = 26^\circ\text{C}$ [27] :

$$\phi_i = h_i(T_i - T_w(x = L, y, t)) \quad \forall y \in [0, H] \quad (2)$$

where the inside convective heat transfer coefficient of the horizontal heat flow is assumed to be $h_i = 7.69 \text{ W/(m}^2 \cdot \text{K)}$ [26].

The initial temperature of all wall configurations is assumed uniform for all layers:

$$T_w(t = 0, x, y) = 25^\circ\text{C} \quad \forall (x, y) \in \{[0, L], [0, H]\} \quad (3)$$

All these boundary conditions are explicitly shown in Fig. 2

Fig. 2. COMSOL heat transfer model geometry, and boundary conditions.

2.2.3 COMSOL multi-physic modeling

The numerical method is based on the finite element method and uses the Galerkin approach [23] to discretize the Heat transfer equations. The external surface of the walls is horizontally oriented and subjected to solar radiation and ambient air convection in the Drâa-Tafilalet region. In order to avoid moving from one PCM phase to another in a short period in any finite element, a $\Delta t = 360$ s time step was chosen for all the simulations of this study. The complete triangular mesh consists of 1644 domain elements and 139 boundary elements as shown in Fig. 3.

Fig. 3. Triangular mesh generation (1644 elements)

3 Results

An analysis of the effect of integrating PCM with distinct median melting temperatures (24 °C, 27 °C, 32 °C, and 37 °C) in clay-straw walls on the heat flux density and temperature at the inside wall surface is presented in summer weather conditions in the Drâa-Tafilalet region. The solar radiation and the outside ambient temperature of Errachidia are shown in Fig. 4 for days of July from 28 to 31.

Fig. 4. Solar radiation (left axis) on vertical south walls and outside air temperature (right axis) in Errachidia on 28-31 July

3.1 Heat flux density at the internal surface of clay-straw walls

In this section, the heat flux density is analyzed to choose the optimal PCM to the Draa-Tafilalet region. Four PCMs with distinct median melting temperatures (24 °C, 27 °C, 32 °C, and 37 °C) are integrated into a clay-straw wall and compared to another without PCM. Figure 5 present the heat flux density at the internal surface of walls integrating different thickness of PCMs layer. For layer thickness of PCM equal to 0.5 cm (fig.5-(a)), heat flux density follows the variations of external conditions except for the first day. In this one, it is clear that walls take heat from the exterior gradually because at $t=0h$ it is night. Then in the next day, the flux never cancels because the walls store the heat inside and release it at night. PCM 37 generates a higher flux than a clay-straw wall without PCM. Therefore, PCM 37 is a bad choice for this region. PCM 24 and PCM 27 have approximately the same heat flux density; they can reduce the heat flux up to 1.8 W/m² than clay-straw wall. PCM 32 has the minimum heat flux value in comparison to the other walls; it can reach a maximum difference equal to 3 W/m². It is shown that for the third and fourth day the peak of the heat flux density of PCM 32 is smaller than the other walls. For layer thickness of PCM equal to 1 cm (fig.5-(b)), similar behaviors in terms of heat flux density can be observed by comparing them to the results of the 0.5 cm thick layer. PCM 37 has the highest heat flux density in comparison with all walls. PCM 24 and PCM 27 can reduce the heat flux up to 1.2 W/m² than the clay-straw wall. PCM 32 has the smallest and most efficient heat flux density value compared to other walls; it can reach a maximum difference equal to 4 W/m². For a PCM layer thickness equal to 2 cm (Fig.5- (c)), some similar behaviors in terms of heat flux density can be noticed by comparing them to the results of the 0.5 cm and 1 cm thick layer. PCM 37 has the highest heat flux density of all the walls. PCM 24 can decrease heat flux by up to 2 W/m² compared to clay straw walls. This time PCM 27 has nearly the same density as the clay-straw wall. PCM 32 has the

minimum and most efficient heat flux density value compared to other walls and can achieve a maximum difference of 5.3 W/m^2 . Finally, in terms of the reduction of heat flux peak, the PCM with a $T_m = 32 \text{ }^\circ\text{C}$ median melting temperature is efficient in the Drâa-Tafilalet region.

Fig. 5. heat flux density at the internal surface of clay-straw walls integrating different PCMs: (a) 0.5 cm thickness of PCM (b) 1 cm thickness of PCM (c) 2 cm thickness of PCM

After we have selected the most appropriate PCM for the Drâa-Tafilalet region, we proceed to the analysis of the optimal thickness at the PCM chosen. Figure 6 presents the heat flux density at the internal surface of walls integrating different thicknesses of the PCM 32 layer. It can be seen that the heat flux density decreases as the thickness of the PCM 32 layer increases. Therefore, the optimal thickness is 2 cm; it is noticed that the peak of this wall is different from the other walls. When the flux increases for all the walls, it decreases for the one with a thickness equal to 2 cm and the opposite. This difference is justified by the fact that the PCM 32 continues the phase change cycle correctly for the 2 cm thickness, whereas at the other thickness the PCM melts quickly and follows the variations of external conditions like insulating material. PCM 32 layer thickness equal to 2 cm can reach a maximum difference equal to 4 W/m^2 . To understand the behavior of PCMs and their importance, a comparative study is presented in the following section.

Fig. 6. Heat flux density (W/m^2) at the internal surface of clay-straw walls integrating different thickness of PCM 32

3.2 Comparison between integration of PCM into cement wall and clay-straw wall

3.2.1 Heat flux density and temperature comparison

In order to analyze the integration of PCM in traditional clay-straw constructions instead of cement constructions; a comparative study is carried out in order to choose the most efficient construction. Figure 7 present the heat flux density (W/m^2) and the temperature ($^{\circ}\text{C}$) at the internal surface of clay-straw walls and cement walls with PCM 32 and without it. The clay-straw construction reduces the heat flow density and temperature compared to cement construction by up to 37 W/m^2 and 5°C respectively. By integrating PCM32 in the cement wall, the heat flux density is reduced with a value up to 28 W/m^2 but it is still higher than the one generated by the clay-straw wall without PCM 32. For this reason, the ancient clay-straw constructions in the Drâa-Tafilalet region are important. By comparing the behavior of the cement wall and that of clay-straw incorporating PCM32, it can be seen that the behavior of the cement wall follows the variations of the external conditions as opposed to the clay-straw wall. For the last one, when the heat flux density increases outside, it decreases inside; which keeps the heat flux density (Fig.7- (a)) and the temperature (Fig.7- (b)) more or less constant because the PCM was partially liquid (partially solid); the phase change is performed.

Fig. 7. The internal surface of clay-straw walls and cement walls with PCM 32 and without: (a) Heat flux density (W/m^2) ; (b) Temperature ($^{\circ}\text{C}$)

3.2.2 Temperature Profile Comparison

In order to understand the effect of the PCM integration in the building envelope, the temperature profile is presented in figure 8. The temperature diffusion is more rapid in cement walls fig.8 (a). It decreases by integrating the PCM32, which stores a large heat quantity inside fig.8 (b). In the opposite situation, the diffusion of temperature is reduced in clay-straw walls fig.8(c) and it is again reduced by integrating the PCM 32, which stores a large quantity of heat inside fig.8 (d).

Fig.8. Comparison between the temperature Profile of different walls: (a) cement wall (b) cement wall with PCM 32 (c) clay-straw wall (d) clay-straw wall with PCM 32

3.2.3 Heat flux reduction

In this section, the reduction in flux density is estimated in percent. Figure 9 shows the heat flux density on the inside and outside of the walls exposed to the weather conditions of the Draa-Tafilalet region. The difference between the outside heat flux density is higher for the cement wall; it is twice as high as that of a clay-straw wall and depends on the properties of the materials. To better, analyze Figure 9, the percentage reduction in heat flux density R (%) (Table 2) is calculated using the following relation:

$$R(\%) = \frac{\varphi_{i(\text{without PCM})} - \varphi_{i(\text{with PCM})}}{\varphi_{i(\text{without PCM})}} \times 100 \quad (11)$$

The integration of PCM 32 in clay-straw wall reduces heat flux density by 44.44% and by 40% in the cement wall. By using the clay-straw construction integrating PCM 32, instead of the cement product construction, the heat flux density is reduced by 80%.

Fig. 9. The inside and outside heat flux density of clay-straw walls and cement walls: (a) Without PCM (b) With PCM 32

Table 2. Heat flux density reduction by integrating PCM 32

Walls		Cement wall	Clay-straw wall
Maximum inside heat flux density (W/m ²)	without PCM 32	50	18
	with PCM 32	30	10
R (%)		40	44.44

4 Conclusion

This paper investigated the integration of phase-change materials (PCM) in clay-straw walls of buildings located in Morocco's Drâa-Tafilalt region. The article deals with the climatic conditions of Errachidia city, corresponding to the Saharan thermal behavior heat flux density. Four PCMs with distinct median melting temperatures (24 °C, 27 °C, 32 °C, and 37 °C) are integrated into a clay-straw wall and compared to another without PCM. In terms of the reduction of heat flux peak, the PCM with a $T_m = 32$ °C median melting temperature is efficient in the Drâa-Tafilalt region. For all wall configurations, the heat flux at the inside surface of the wall, for the four days of July (28-31), was constant when the PCM was partially liquid (partially solid) and followed the outside conditions when the PCM was completely solid or liquid. By using the clay-straw construction integrating PCM 32, instead of the cement product construction, the heat flux density is reduced by 80%.

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