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Numerical study of thermos physical properties of a hollow brick filled by the PCM

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Abstract

In this paper a numerical study of the thermos physical properties of the new material used in building is presented. The material proposed is the hollow brick with two kind of size, filled by phase change material of the paraffin kind in hollow area. The latter may increase the thermal inertia of the external walls in buildings. The numerical work used is based on the finite elements method. This study allows an approach on thermos physical properties for the proposed material, such as the effective thermal conductivity, the equivalent heat capacity, evaluation of heat flux and temperature fluctuation in indoor surface of the wall. The results obtained show that the hollow brick with paraffin could be a solution to increase thermal and energy efficiency in buildings.

1. Introduction

The Thermal energy can be stored and retrieved by changing the internal energy of a material in the form of sensible heat, latent heat, by thermo-chemical process or by combination of these forms [1]. the examples of thermal energy storage (TES) can be found in solar heat storage for heating in buildings in winter and storage of cool energy generated by cooling in summer [2].

Among above thermal energy storage systems, latent heat storage system using of phase change materials (PCM) is most promising technique, due to its advantages of high energy storage density and small variations temperature from storage to retrieval [3-4]. Furthermore, not only have these materials been used in thermal storage devices for heating and air cooling setups, but they can also be integrated into the building envelope in order to increase its thermal mass and thus reduce indoor temperature fluctuations. This passive latent TES has both a beneficial effect on reducing energy consumption for heating and cooling and on improving the thermal comfort of occupants.

There are various ways to use PCM in the passive and active storages for building applications i.e. PCM can be encapsulated in concrete, wallboard, shutter, ceiling and floor. The PCMs having the melting/freezing temperature in the range between 20 to 32°C are more suitable for building applications [5]. Comprehensive information about the passive applications of PCM in building systems can be found in [6], as well that the different PCM and techniques for their integration into building elements are extensively reviewed in [7-8].

The correct design of the building or storage system with integrated PCMs requires correct knowledge of the thermal properties of the PCMs used. For example, the single data points, the phase change enthalpy at the melting temperature or the heat of fusion don't describe PCM properties with sufficient accuracy to perform dynamic simulations of a room or a whole building containing PCM.

The phase change occurs in a temperature range and not at a constant temperature level, and therefore specific heat capacity or enthalpy of this type of material has to be known as a function of temperature. Literature reviews indicated that the following methods are most often used to measure specific heat capacity of pure PCMs and their composites: differential scanning calorimetry (DSC) and T-history method [9-11]. This method can only be applied to measure the thermal conductivity of the PCMs whose phase-change process is one clear interface between two phases in deed, for some salt hydrates this condition cannot be met.

In Algeria, lot of dwellings are built with exterior cavity walls, for this reason this work is based on the presentation of a numerical study to determine the thermos physical proprieties of two types of hollow brick proposed for building walls with using COMSOL [12] based on the finite elements method. The thermal effectiveness of the proposed brick-PCM system is evaluated by comparing the fluctuation of temperature and heat flux at the indoor surface to a wall without the PCM with proposed boundary conditions.

2. Description of materials:

The red hollow brick used is the parallelepiped form with two kind of size (Figure 1): The Brick Type 1 it is consisted of eight internal empty holes with the total dimension thickness=10cm, width=20cm and length 30 cm. The Type 2 it is consisted of twelve internal empty holes with thickness=15cm, width=20cm and length 30 cm. For each cavity in the two types has a parallelepiped section (3.5 x 3.5 cm²) and 30 cm in length. It is proposed to insert the material phase change in particular the paraffin (n-octadecane) in internal cavities.

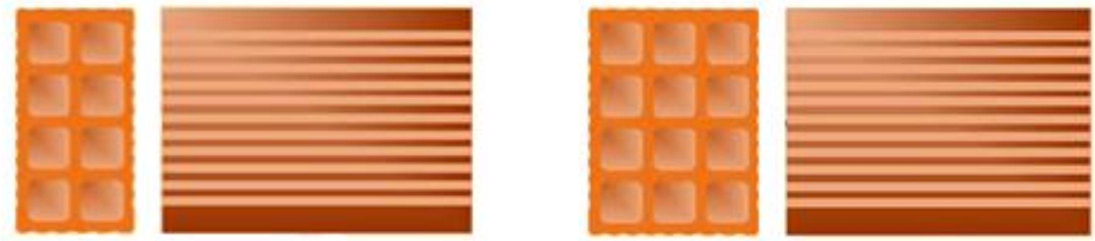

Figure 1: Two types of hollow brick wall, left: type1 (8 hollows) and right: type 2 (12 hollows).

The composition of the paraffin-polymer mixture is optimized so as to completely eliminate the potential leakage of the PCM in the liquid state. To the melting phase, the onset temperature is 26°C, the temperature at the peak is 27.6°C and latent heat of fusion is 243.5kJ /kg. These values are consistent with the results already achieved and those in the literature [13]. The thermos physical characteristics of hollow brick and PCM are shown in Table 1.

3. Governing Equations and method of solution:

The main assumptions considered in this study are: heat transfer is unsteady and one-dimensional. The PCM material used is pure, homogeneous and isotropic. All thermos physical properties were kept constant but may be different in the liquid and solid phases (conductivity and specific heat) and without convective heat-transfer in the liquid PCM phase. The interfaces layers between the hollow brick and the PCM are homogeneous with perfect contact between them, which means that contact resistance is neglected. The implementation of the enthalpy balance is:

$$\rho C \frac{\partial T}{\partial t} + \varepsilon \rho L_f \frac{\partial f}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \quad (1)$$

With:

ε=0: The case of a construction or PCM material (liquid or solid phase)

ε=1: PCM molten at $T = T_m$, characterized by its title molten m.

The system of equations (1), associated with the boundary conditions in internal and external surfaces is solved numerically using the finite element method with COMSOL software.

In order to overcome definition of phase change, the equivalent heat capacity and whatever T and even with phase change are respectively defined by:

$$C_{pe}'(\mathrm{T}) = \frac{\partial h}{\partial T} \quad (2)$$

$$h = h_r + \int_{T_r}^{T} C_{pe}'(\mathrm{T}) \times \partial T \quad (3)$$

In our case, only a fraction f of material changes here its state therefore the equivalent heat capacity condition can be written:

$$C_{pe}' = C_p \pm L_f \times \frac{\partial f}{\partial T} \quad (4)$$

For both type of hollow brick with and without PCM, the formula (5) is used to find the total of heat stored during melting:

$$Q = m \times (h_f - h_i) = m \times \Delta h_m \text{ (kJ)} \quad (5)$$

The heat stored only by PCM can be evaluated with a subtraction between the total heat stored in the hollow brick filled by PCM with the total heat stored by the reference case (the heat stored by the air was neglected). The results of the latent heat during melting are obtained by:

$$Q_{PCM} = (f_S \times Cp_s \times \Delta T_s + f_l \times Cp_l \times \Delta T_l) + L_f \quad (6)$$

When the material is heated, and the PCM liquefies, ΔT_s is equal to the melting temperature minus the initial temperature of the test material (T_m - T_i) and is equal to the final temperature of the test minus melting temperature of the material (T_m - T_i) and ΔT_l is ($T_f - T_m$) To determine the thermal conductivity in the solid state, it's required to impose a temperature difference between two faces of the material until reaching the steady state [14-16].

The relations below provide faster access to the value of the effective conductivity in the solid and liquid state:

$$\lambda_{eff\ S} = \frac{\varphi \times w}{\Delta T_s} \quad (7)$$

$$\lambda_{eff\ l} = \frac{\varphi \times w}{\Delta T_l} \quad (8)$$

With w thickness of material and ΔT_s is the difference temperature between T_{os} and T_{is} when $T_{os}, T_{is} < T_m$. ΔT_l is difference temperature between T_{os} and T_{is} when T_{os}, $T_{is} > T_m$.

4. Numerical validation:

In this section, a validation code is made with experimental results for a case study of another kind hollow brick filed by PCM available in [17]. The dimensions of this material are given in Figure 2. The experimental setup consists to impose a linear temperature on the right face of hollow brick witch increased from 21°C to 52°C for a period of 6 hours (Rate of rise = 0.1°C /min) followed by uniform temperature at 52°C for 4 hours. The other face is directly in contact with laboratory air whose temperature is stabilized at about 21°C during the experiment. The other faces are surrounded by a polyurethane foam with thickness=3cm. The melting temperature is about 29.2°C and the latent heat of fusion is 131.7 kJ/kg. We note that a mesh study was carried out and we opted for a quadrilateral mesh of 1044 elements with convergence criterion for temperature is 10^{-4}.

Table 1: Characteristics of PCM and hollow brick

Material	Density (kg/m^3)	Thermal Conductivity (W/m.°K)	Heat capacity (J/kg.°K)
PCM (solid)	865	0.358	1934
PCM (liquid)	780	0.148	2196
Hollow brick	1600	0.7	840

In figures 3 show the comparison between our numerical results with those obtained in the experimental [17] on the variation of the temperature in the right face of the hollow brick with PCM.

When the temperature is lower than the temperature of melting of 29°C, the numerical result agrees well with the experimental results [17], but when the PCM transforms to its liquid state, it's observed that the temperature deduced numerically increasing more rapidly than the experimental one. This can be explained by the presence of natural convection in the experimental cases and by the presence of the third dimension by against we neglect its effect in our numerical study in two dimensions. In a general way, we see that our numerical model is valid to predict results which are closer to reality when the natural convection in the liquid phase of PCM will be neglected.

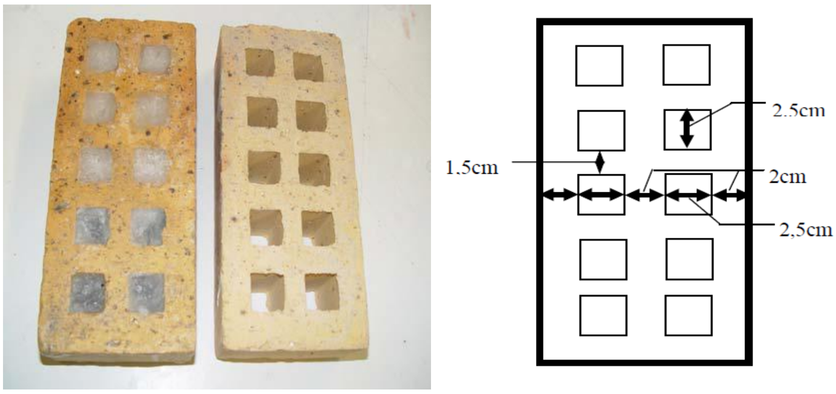

Figure 2: Dimensions of the hollow brick [17].

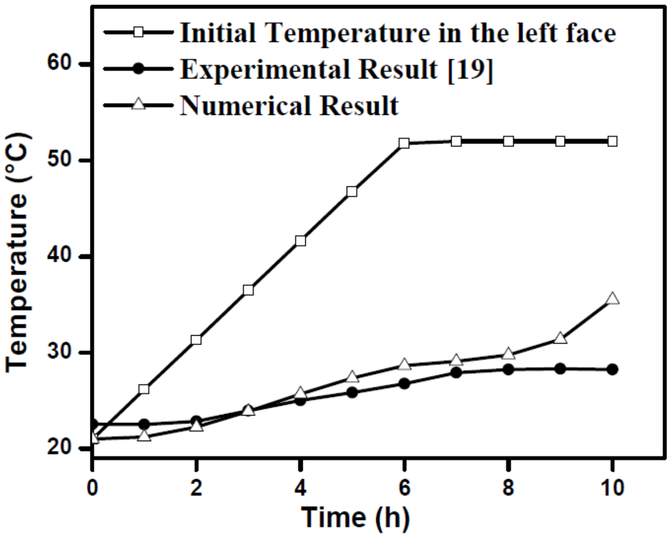

Figure 3: Validation with the temperatures at the interfaces of the hollow brick of reference [17].

5. Results and Discussion

In this section the indoor environment is still considered held at a constant temperature T_{is}= 20°c. On the outer face of the wall is imposed a linear increase in temperature from 20 ° C to 50 ° C for 15 hours (up shift = 2 °C/h) then the temperature is maintained from the outside at 50 ° C for 9 hours. To clarify the influence of PCM, a comparative study was established between the temperature in the two sides of the hollow brick (of type 1 and type 2). In the first case, the hollow brick is incorporated by PCM and in the second part is the reference case i.e., the material without PCM. The result of this comparison is shown in Fig.4 and 5. For calculation,we note that the convergence of numerical method is also tested by varying the effects of mesh sizes and also the relative time step and analyzing their effects on results. A quadrilateral mesh is adopted with 800 elements for Brick of type 1 and 1200 elements for the type 2 are used. The function used for interpolation of temperature inside a finite element is Lagrange quadratic, in which the shape function coefficients are constrained so that the solution is continuous across boundaries between adjacent elements. The convergence criterion for temperature is 10^{-4}.

5.1 Preliminary analysis:

It is found in the two types of brick that reaches temperature level in the reference case is higher than walls with PCM for the similar conditions. This numerical study clearly highlights the effect of PCM on the thermal inertia of this walls, the variation of temperature in the wall with PCM is much slower. The temperature level achieved over a period of 24 hours was lower when the PCM is present this is due to the difference of the thermal losses in the two walls.

It is also noted that after a period of 24 hours the temperature in the inner surface of the hollow brick wall type1 with PCM has reached a value of 30 °C by slightly different contribution to the hollow brick of type 2 with PCM which the temperature reaching equal to 33 °C. This small temperature difference can be explained by the fact that the state of the changes phases total of PCM in the two walls will be almost the same for a period of 24 hours. According to Figure 4, it can be observed that during the period from 10 to 20 h, the PCM inserted in the hollow brick type 1 moderate the indoor surface temperature swings and keep it close to the melting temperature. This can be explaining by the beginnings of the melting process which permits the storage a large energy with less temperature variation in the hollow brick. As a result, this phenomenon will create a large difference in a profile between outside surface and the inside. At the end of this measuring, it can be seen that the profile of the indoor surface temperature is started to take another path upwards. This slop variation can be used as an indicator on the end of the phase change process. In the Figure 5 and compared to the first type, the indoor surface temperature of the hollow brick with PCM has taken a longer time (about 16 h) in order to reach the melting temperature which means that in this case, there is a delay in the beginnings of the melting process.

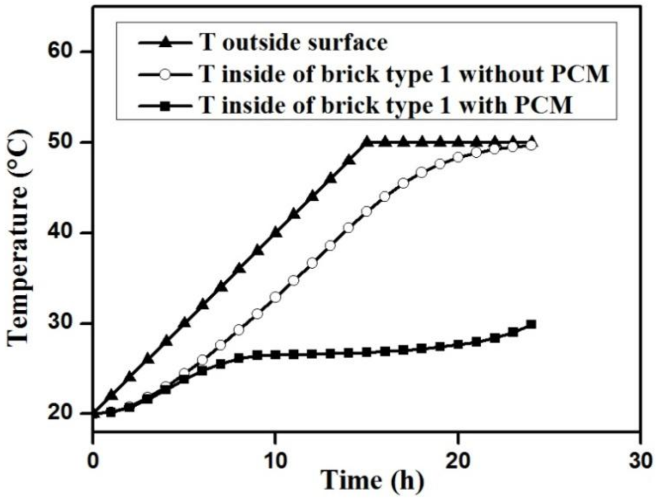

Figure 4: The variation of temperature surfaces with time (hollow brick Type 1)

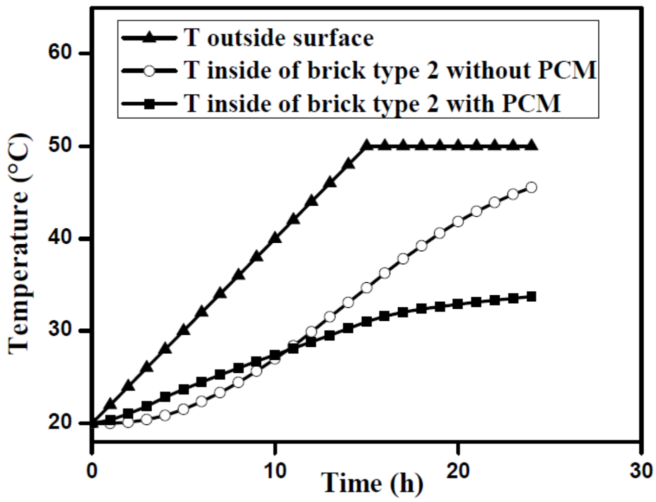

Figure 5: The variation of temperature surfaces with time (hollow brick Type 2).

5.2 Thermos physical properties of the hollow brick with PCM:

To confirm these preliminary analyzes it is necessary to determine the thermos physical properties in the two types of walls. In first, the equation (5) is used to deduce the total heat stored in the both type of the hollow brick (Table 2). It's found that the heat for the hollow brick of type1 with PCM is about 734.36 kJ and for the reference case (without PCM) it is around of 77.72kJ. And for hollow brick of type 2, the wall with PCM stores about 748.9 kJ and 89.28 kJ in the reference case.

It is clearly seen that almost(most) of the heat is stored as latent heat which explains reason that the fluctuations of temperature in the inside face of the wall with PCM is much slower. For both hollow brick, the difference between the heat flux in the external and internal surfaces of walls with and without PCM is studied. Their results are presented in Figure 6 and 7.

The results indicate that the decrease heat transmitted is very important in both hollow bricks with PCM compared to the reference case and this is due to the large accumulation of heat. A comparison between Figure 6 and 7 could explain that due to the difference between the quantity of PCM inserted in the hollow bricks; The hollow brick type 2, contains 1/3 more of the amount of PCM compared to the brick type1, which increase energy required for the phase change process. To estimate the heat value stored by PCM, a subtraction between wall with PCM and reference wall is done with neglecting the heat stored by air in the wall without PCM. The table2 summarizes the results of heat stored in 24 hours by the two types of brick walls with and without PCM.

Table 2 The heat stored in tow walls

The total heat stored	Brick Hollow Type 1	Brick Hollow Type 2
Q_{tot} (kJ) (wall with PCM)	734.36	748.9
The total heat stored Q_{tot} (kJ) (wall without PCM)	77.72	89.29
The heat stored by PCM Q_{PCM} (kJ)	656.64	659.62

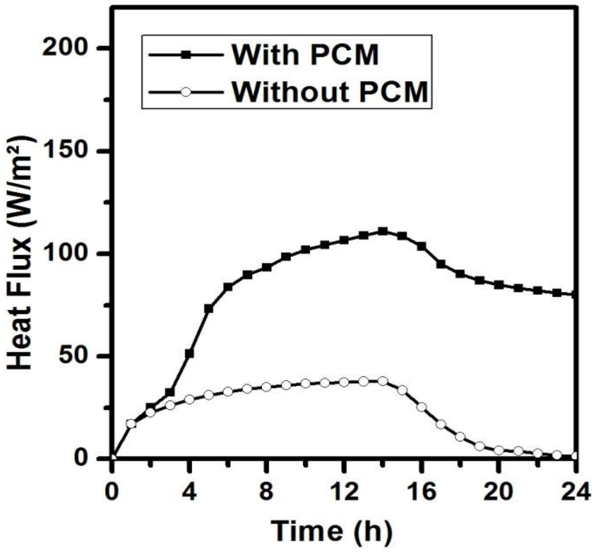

Figure 6: The difference in the heat flux for hollow brick to type 1

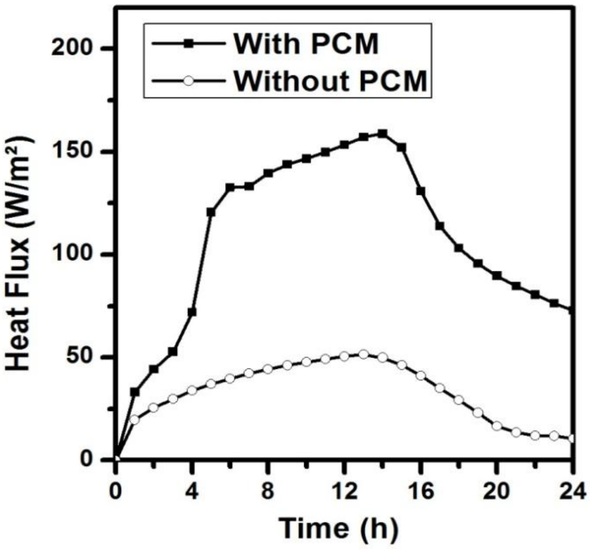

Figure 7: The difference in the heat flux for hollow brick to type 2

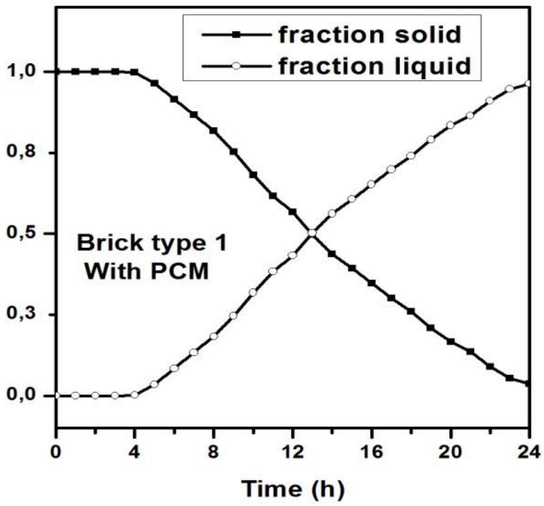

Figure 8: Fraction (solid/ liquid) during melting according time in brick to type 1.

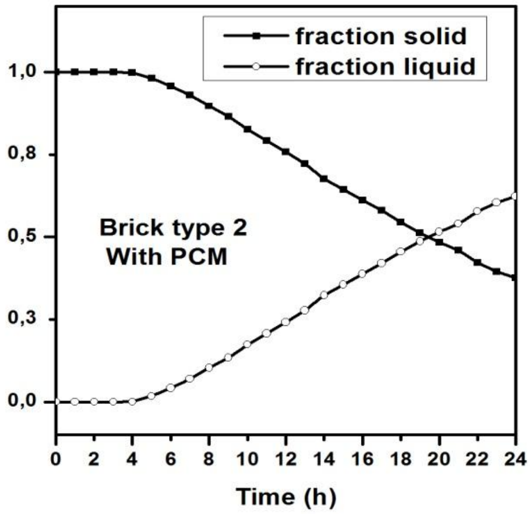

Figure 9: Fraction (solid/ liquid) during melting according time in brick to type 2.

Table 3 Latent heat in (kJ/kg) in two walls

Latent heat	Hollow Brick Type 1+PCM	Hollow Brick Type 2+PCM
Q_{PCM} Total (kJ/kg)	287.38	190.85
Q sensible (kJ/kg)	32.015	27.29
The latent heat L_f (kJ/kg)	255.37	163.29

In the Figure 8 and 9 are presented the values of the fraction solid/liquid of PCM according to time during melting. By using the results of this fraction and based on the equation (6) and the values in Table 2, the latent heat can be deduced. The results of latent heat stored by two types of hollow brick are shown in the Table 3.

When the brick type 1 is used, the PCM will be completely in the liquid state after a period of 24 hours; this change of phase can obviously increase the equivalent specific heat of material between in the range of melting temperature. However, in the second case of the brick type 2 and after the same period as the first there remains a total of PCM in solid state which absorbs more energy so that it can change phase. Compared to the first model, this loss of energy in the brick type 2 will cause a delay to achieve the temperature range where the equivalent specific heat will be varied.

The equivalent heat capacity of the two type's walls of hollow brick with PCM is calculated with the equation (4). Their values are shown in the Figure 10 and 11. It's observed a strong augmentation of C_{pe}' in the two types of hollow brick during the melting process of PCM. For the first type the value of C_{pe}' is varied from 27°C to 30°C and for the second type is from 30 °C to 34°C.

The effective thermal conductivity of the two types of hollow brick is deduced by equation (7) and (8) and the results for the both phases are shown in Table 4. The small difference between the effective value of the thermal conductivity of the hollow brick type 1 and that of the hollow brick type 2 can be explained by the fact that the two types of hollow bricks contain practically the same volume fraction of PCM in The solid phase.

When the PCM is reached its liquid phase, its thermal conductivity will be decreased which leads to reduce the effective thermal conductivity of the composite hollow brick-PCM.

Table 4 The effective thermal conductivity

λ_{eff} (W/m.°K)	Brick Type 1+PCM	Brick Type 2+PCM
solid phase	0.5	0.47
liquid phase	0.33	0.35

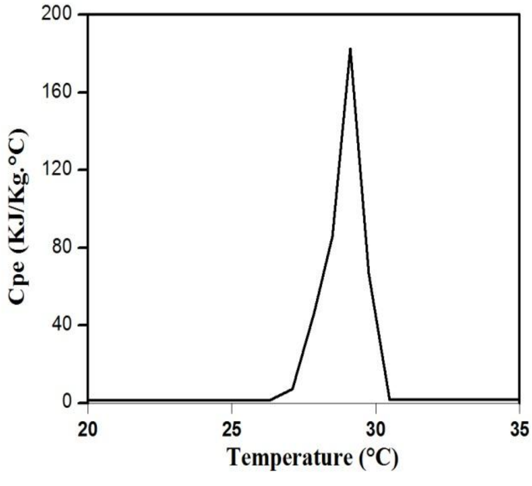

Figure10: The equivalent thermal capacity of brick Type 1

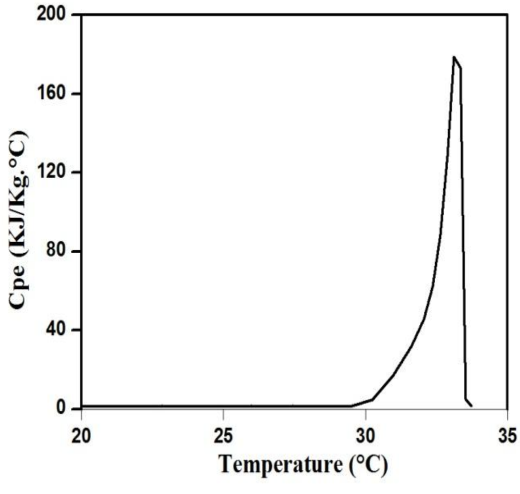

Figure 11: The equivalent thermal capacity of brick Type 2

Conclusion

The study outlined in this article is part of a project whose ultimate objective is to allow a passive regulating of the temperature inside a building. The proposed solution to achieve this objective is the incorporation of a phase change material in the construction elements.

A numerical simulation based on the finite element method is used to study the thermal characteristics in the melting process of a phase change material (n-octadecan) incorporated in two types of hollow brick and compare it with the reference case without PCM.

We noticed that the steady state is reached much later when the wall is filled with PCM. Paradoxically, the material being introduced is more heat conductive than the wall without PCM. This result is explained by a large accumulation of heat in the PCM particularly when phase changes. This study made it possible to calculate the thermos physical characteristics of the brick filled by the phase change materials from a numerical simulation. the calculation also made it possible to determine the total of heat storage by latent heat during melting and the interface temperatures. The results of this study show that the proposed material could be one of the solutions to improve energy efficiency in buildings.

Nomenclature

A : area (m²)
C_p : specific heat capacity (J/kg·K)
f : the melted fraction
h : enthalpy (J/kg)
L_f : latent heat of fusion, (J/kg)
Q : the total of heat (kJ)
T : temperature (°C)
t : time (h)
w : thickness of material (m)

Greek symbols

ρ : density (kg/m^3)
φ : heat Flux (W/m²)

Subscript

e : equivalent
eff : effective
f : final
is : inside
l : liquid
m : melting point
os : outside

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