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Modeling of Heat Transfer in a Habitat Built in Local Materials in Dry Tropical Climate

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Authors' contributions

This work was carried out in collaboration between all authors. Authors AC, BZ and DJB designed the study, performed the numeric analysis, wrote the protocol and wrote the first draft of the manuscript. Authors BD, XC and SA managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

A numerical modeling of heat transfer in a habitat whose walls are in local materials (compressed earth blocks) is presented. The transfer equations based on the nodal method are solved by an implicit finite difference method and the Gauss algorithm coupled to an iterative procedure. It was analyzed the influence of the rate of air exchange, the thickness of the walls and the nature of the materials of which they are composed on the spatio-temporal distributions of the temperature of the air inside the habitat and those of its walls. The results show that the temperature inside habitats whose walls are made of local materials (earthen materials) is lower than that of modern habitats (cement blocks). The increase in the thickness of the walls contributes to a better thermal inertia of the habitat by improving the decrement factor and the time lag difference between the inside and the outside. Also, over-ventilation of a habitat with high inertia has a negative impact on its performance during the hottest periods.

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Keywords: Thermal inertia; ventilation; time lag; decrement factor; thermal modeling.

NOMENCLATURES

DFS	*: Density of the solar flux absorbed by the material,* $W.m^{-2}$
T_a	*: Air temperature,* ^0C
T_s	*: Temperature of wall surface,* ^0C
V	*: Volume,* m^3
h_c	*: Coefficient of heat transfer by convection,* $W.m^{-2}.K$
h_r	*: Coefficient of heat transfer by radiation,* $W.m^{-2}.K$
A	*: Area,* m^2
f	*: Reduction factor*
ϕ	*: Time lag,* h
ρ	*: Density,* kg / m^3
C_p	*: Thermal mass capacity,* $J.kg^{-1}K^{-1}$
α	*: Absorptivity coefficient*
$\max$	*: maximum*
$\min$	*: minimal*
e	*: external*
i	*: internal*

1. INTRODUCTION

The building sector is one of the top three energy consumers in the world, with transportation and industry [1]. The share of energy consumption in buildings amounts to 40% of world energy [2] and 50% of this consumption is devoted generally to heating, ventilation and air conditioning systems [3]. The thermal design of a building influences the thermal performance of the building, which also affects energy consumption [4]. Reducing energy consumption in buildings requires a good design of its envelope. The thermal performance of a building can be improved by acting either on its physical form, its solar protections [5,6] and its orientation [7], or on the composition of the materials of its envelope (improvement of the thermal inertia). Kabore M. [8] studied the influence of the type of roofing of buildings on their thermal performance in tropical climate and showed that the use of an insulator with a good reflection coefficient effectively fights against heat gains at the level of the roof. Ouedraogo I. [9] realized a numerical study of a bioclimatic roof favoring ventilation to reduce thermal loads in a habitat in dry tropical climate in Burkina Faso; from this study it appears that a north-south orientation along the roof and an inclination of 50° of the roof improve its ventilation. It was demonstrated during a numerical study of the characteristics of the envelope of a typical Malaysian building that the energy consumption of a building oriented north-south is reduced by 10% compared to that of the same East-West building [5]. It was demonstrated in a numerical study carried out by Bojic that an external thermal insulation of building walls contributes to a reduction of around 20% in annual building energy consumption [10]. E. Stéphan highlighted the impact of the thermal inertia of traditional buildings in summer, and concluded that this inertia was variable depending on where the building is located and its thermal insulation. A. Gagliano and al. [11] have shown that high thermal inertia in the building in combination with natural ventilation can reduce overheating phenomena in the building. In addition, the time lag difference between the temperature of the outer face and that of the inner face of the wall can be increased by 5 hours when the orientation of the building passes from west to east. In sub-Saharan Africa, the design of modern buildings is not always adapted to the climatic context of the area [12]. This results in excessive energy consumption in the building sector. Modeling and simulation of the thermal performance of a bioclimatic habitat model in a humid tropical climate showed that the indoor temperature reached 28.3°C [13].

The studies mentioned above show that thermal inertia and ventilation contribute to the reduction of expenses in air conditioning in buildings for climates where daily variations in temperature are high [14,15] such as those of Ouagadougou (Fig. 1). The objective of this work is to contribute to the improvement of the thermal performance of a habitat in local building materials located in hot and dry tropical climate. We first present a numerical modeling of thermal transfers in a habitat built in blocks of compressed earth located in the city of Ouagadougou. Then, we analyze the influence of three types of materials and different thicknesses of these materials on the spatio-temporal distribution of temperatures in the habitat. Finally, we evaluate the influence of the thermal inertia of the habitat envelope on the evolution of temperatures according to the rate of air exchange in the habitat.

2. HABITAT MODELING

2.1 Description of the Habitat

The habitat model considered is composed of a room with a roof. It is a room with a 5x4m floor and a height of 3 m whose main façade is oriented north (Fig. 2). It has a window with 1x1 m dimension, a rectangular door (2x1 m) and a false ceiling topped with a roof inclined at an angle of five degrees to the horizontal. The habitat model is like a parallelepipedic enclosure surmounted by a trapezoidal enclosure which represents the roof. The walls are constructed with agglomerates of Compressed Earth Blocks 18cm thick or cement block with a coating on the inner and outer side 2 cm thick. The inside of the wall is covered with white paint. The roof is a complex consisting of plywood false ceiling 2 cm thick and a roof made of galvanized steel sheet 1 mm thick. The thermo-physical properties of the building envelope are given in Table 1.

2.2 Mathematical Formulation.

2.2.1 Simplifying hypotheses

Let's put the following simplifying assumptions:

- Conduction heat transfers are unidirectional;
- Air is assimilated to a perfect gas perfectly transparent to solar radiations;
- The materials are assimilated to gray bodies;
- Internal sources of heat are nil;
- The thermo-physical properties of the materials used are constant.

The method adopted for describing the thermal behavior of the habitat model is based on nodal analysis [16,13]. In general, if we consider a given node (i) of a habitat component, the instantaneous variation of energy within this component is equal to the algebraic sum of the heat flux densities exchanged through this medium. It is written:

$$\frac{m_i.C_{p_i}}{A}.\frac{dT_i}{dt} = DFS_i + \Phi_i + \sum_i \sum_j \Phi x_{ij} \quad (1)$$

With:

T_i : Temperature or potential of the material (i)

DFS_i : Density of the solar flux absorbed by the component (i) ($W.m^{-2}$)

$$DFS_i = \alpha_i.\varphi_i \quad (2)$$

α_i : Absorbance coefficient of the component (i)

φ_i : Density of incident flux on the component (i) ($W.m^{-2}$)

Φ_i : Flow density of the heat source of the component (i) ($W.m^{-2}$)

Φx_{ij} : Flow density exchanged according to the transfer mode between nodes (i) and (j) ($W.m^{-2}$)

$$\Phi x_{ij} = h_{x_{ij}} (T_j - T_i) \quad (3)$$

$h_{x_{ij}}$: Coefficient of exchange between nodes (i) and (j) of the component ($W.m^{-2}.K$)

2.2.2 Transfer equations

Taking into account the simplifying hypotheses formulated above, the application of equation (1) to the different environments of the habitat model leads to:

- air

$$\rho_a.C_p.\frac{\partial T_{a_i}}{\partial t} = \sum_j A_j h_{c_j}\left(T_j - T_{a_i}\right) + n.V.\rho.C_p\left(T_o - T_{a_i}\right) \quad (4)$$

- walls
- External face

$$\frac{\rho_{se}.C_{p_{se}}}{S_e}.\frac{\partial T_{se}}{\partial t} = h_{ce}\left(T_{ae} - T_{se}\right) + h_{r_{ciel}}\left(T_{ciel} - T_{se}\right) + h_{r_{sol}}\left(T_{sol} - T_{se}\right) + K\left(T_{si} - T_{se}\right) + DFS_{se} \quad (5)$$

- Internal face

$$\frac{\rho_{si}.C_{p_{si}}}{S_i}.\frac{\partial T_{si}}{\partial t} = h_{ci}\left(T_{ai} - T_{si}\right) + \sum_n h_{r_{se,n}}\left(T_n - T_{se}\right) + K\left(T_{se} - T_{si}\right) \quad (6)$$

In order to compare the thermal performance of the building envelope according to the material used, we consider some dynamic parameters such as the decrement factor and the time lag [17,18]. These two parameters make it possible to better characterize the inertia of buildings [11] while taking into account the convective exchanges with the walls. The expressions of these parameters are:

- Time lag (hours)

$$\phi = t_{T_{i,\max}} - t_{T_{e,\max}} \quad (7)$$

With: $t_{T_{i,\max}}, t_{T_{e,\max}}$ respectively the times at which the maximum indoor and outdoor temperature amplitudes are reached.

- Decrement factor

$$f = \frac{\Delta T_i}{\Delta T_e} = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \quad (8)$$

With: ΔT_i , ΔT_e respectively the maximum amplitudes of the indoor and outdoor temperature.

Equation (8) shows that the habitat better dampens maximum temperature values when the decrement factor is low.

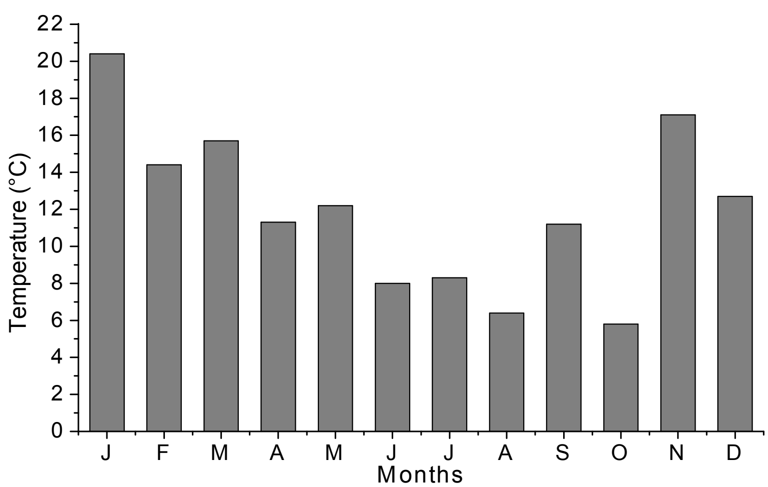

Fig. 1. Mean variations in ambient temperature (Ouagadougou)

Table 1. Thermo-physical properties of materials [8,19]

Materials	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Density (kg/m^3)
Cement agglomerate	0.833	1000	1000
Galvanized steel sheet	50	480	7800
Mortar-coated	1.15	1000	1700
Concrete	1.4	840	2240
Compressed Earth Blocks	0.671	1492	1960
Raw Earth	0.556	1417	1835

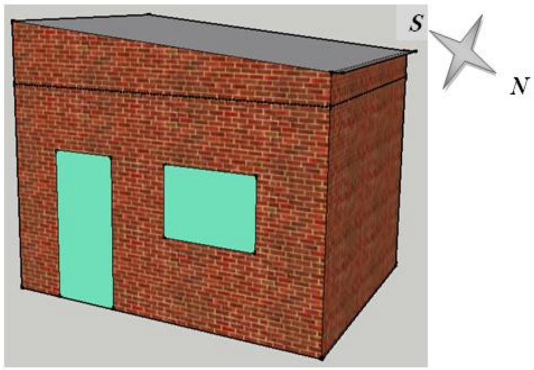

Fig. 2. Perspective of the habitat used

2.3 Resolution Method

Equations (4), (5) and (6) are discretized by an implicit finite difference method. The expressions thus obtained are put in the following form:

$$C\frac{T(t+\Delta t)-T(t)}{\Delta t}=AT(t+\Delta t)+BU(t+\Delta t) \quad (9)$$

The systems of algebraic equations obtained are solved by the Gauss algorithm coupled to an iterative procedure because heat coefficients by radiation and convection depend on the temperatures of the different areas which are the unknown of the problem.

2.4 Climate Data

In order to obtain climate data that are representative of the average climate of the city of Ouagadougou, we use the concept of a typical year developed by Ouedraogo et al. [20] with the Sandia laboratory method from meteorological data of the city of Ouagadougou over a period of 15 years (Fig. 4). We observe in this typical year, that the values of the ambient air temperatures are very high during the months of March, April and May. The ambient temperatures are relatively low during the winter period and at the end of the year. Fig. 5 shows the evolution of global horizontal solar flux density and ambient air temperature for the typical April day. Indeed, the month of April is the hottest time of the year for the city of Ouagadougou. The density of the flux reaches a maximum value of 974W / m2 at 12 o'clock and maximum value of the ambient temperature is 40.6°C at 15 o'clock. We therefore choose the climate data of the typical day in April to analyze the thermal behavior of the habitat for extreme weather conditions.

3. VALIDATION OF THE MODEL

In order to validate our numerical code, we applied our model to that of nganya et al. [13] for the city of douala in cameroon located in the hot tropical climate. A comparison between the temperature distributions given by our model and those of nganya shows a good qualitative and quantitative similarity (Fig. 6). Indeed, the maximum relative difference does not exceed 3.5%. This difference can result from the correlations that we used for the calculation of convective heat transfer coefficients.

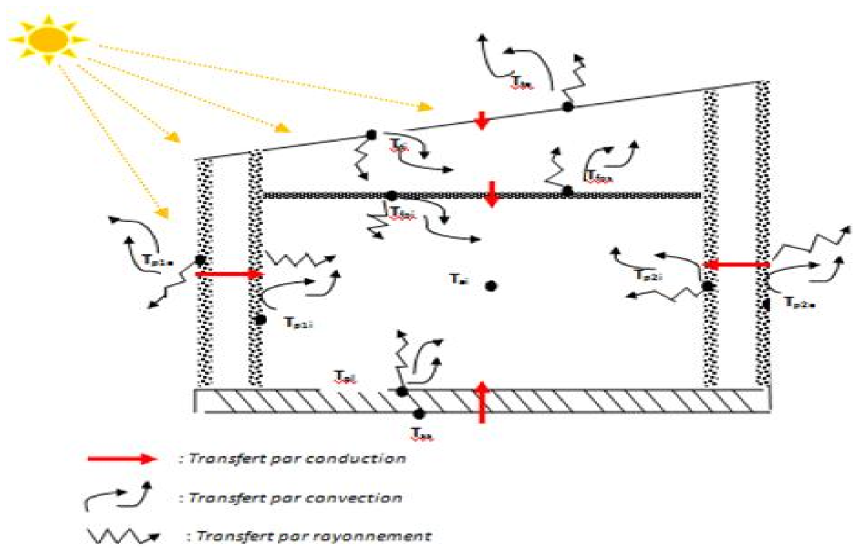

Fig. 3. Diagram of heat transfers in the habitat

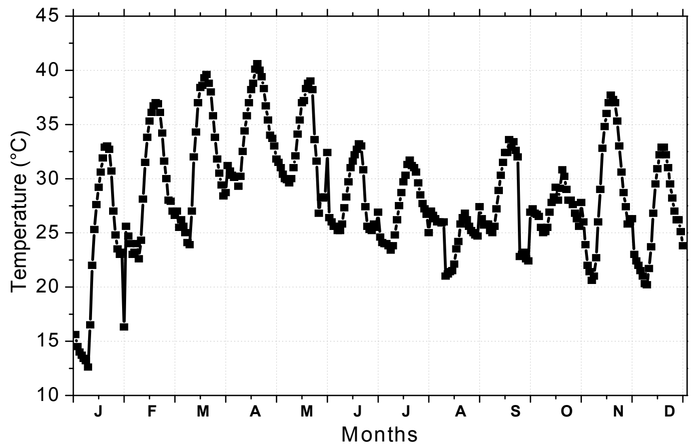

Fig. 4. Ambient temperature of the typical year [20]

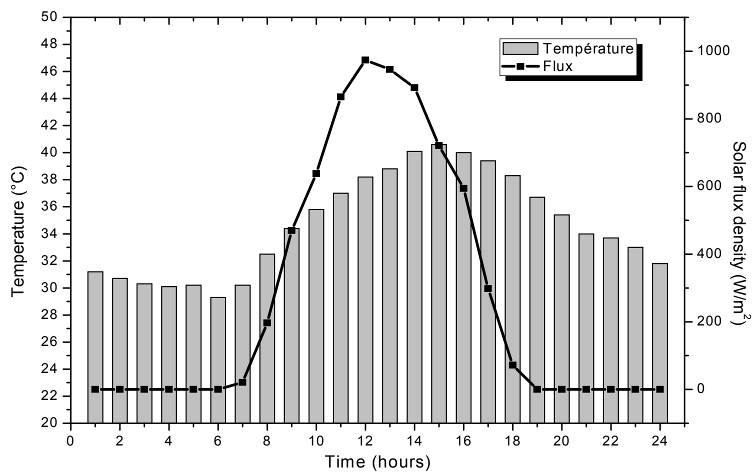

Fig. 5. Overall solar flux density and ambient temperature of the typical April day

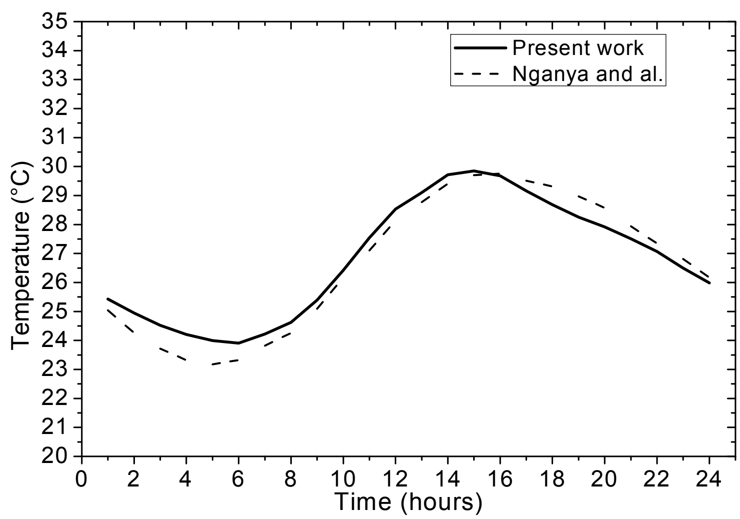

Fig. 6. Comparison of temperature profiles

4. RESULTS AND DISCUSSION

4.1 Temperature Profiles of the Different Components of the Habitat

Fig. 7 shows the evolution over a day of the indoor air temperature (Tai), the inner face of the north wall (Tmni), the false ceiling (Tfp) and the roof (Ttoit) of the habitat. As has been shown by many authors [21,8,9], in sub-Saharan Africa, roofing is the component of the habitat with the highest heat loss and heat input. Indeed the maximum temperature of the habitat is observed at the level of the roof which reaches 58°C at 12 o'clock (Fig. 4).

It should also be noted that during the day the evolution of the temperature of the air inside the habitat is similar to that of the outside air. Attenuation can be observed between the maximum temperatures of outdoor air and indoor air of the habitat during the day with a maximum difference of 6°C at 15:00 (Fig. 7). An analysis of the evolution of the temperatures at the level of the false ceiling and the roof shows that the roof generates an attenuation of the impact of the solar flux on the temperature of the interior air of the habitat. Indeed, the temperature of the false ceiling is significantly lower than that of the roof.

The temporal evolution of the temperature of the outer face of the habitat wall is similar to that of the inner face (Fig. 8). However, the thermal inertia of the material compressed earth blocks of which the wall is made causes a temporal phase shift all the higher as the heat flux captured by this wall is important. Thus, the maximum value of this phase shift is 5 hours (14:00 -19:00).

4.2 Characterization of the Thermal Performance of the Building

We analyze the influence of the nature of the materials of the walls of the habitat, during the typical day of April, on the evolution of the temperature of the indoor air (Fig. 9). On the one hand, these habitats are built, in modern building materials (hollow cement blocks) and on the other hand, in local building materials (compressed earth blocks and raw earth). It should be noted that between 9:00 am and 24:00 pm, the air temperatures inside the habitats whose walls are made of local materials are lower than those in the hollow cement block habitat. In addition, the maximum value of the temperature reached in the cement block room is 38.5°C. They are respectively 35.5°C and 35°C, in the premises whose walls are raw earth and compressed earth blocks. This result is explained by the thermal properties (density, heat mass, conductivity ...). In fact, the compressed earth blocks and the raw earth have a high thermal inertia compared to that of the cement block. It follows that the reduction of the thermal loads of the earth constructions is greater than that of the concrete block constructions.

We can therefore conclude that local construction materials such as raw earth or compressed earth blocks have a higher thermal inertia than cement block.

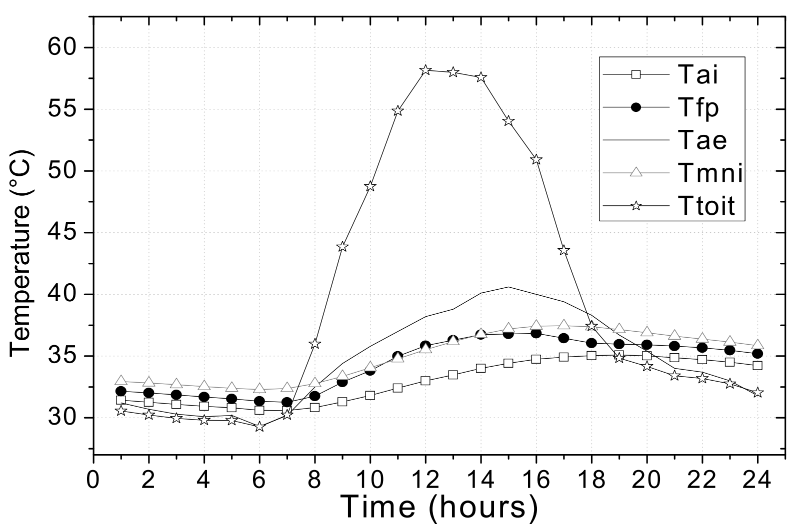

Fig. 7. Evolution of temperature profiles on certain components of the habitat

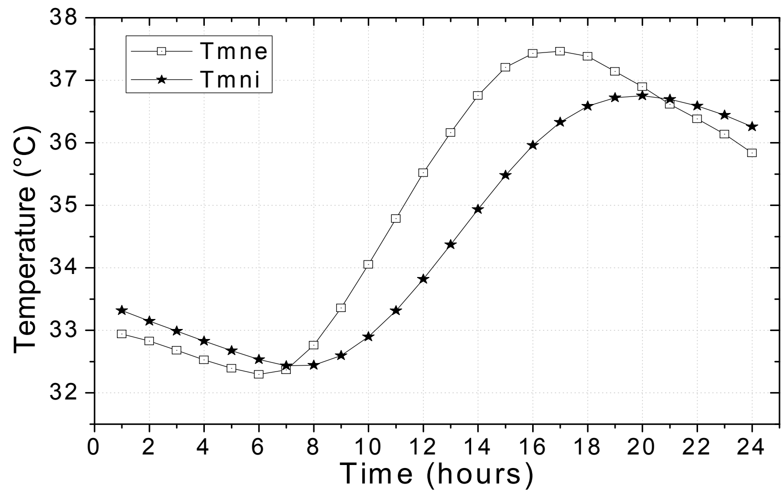

Fig. 8. Evolution of temperature profiles on the external and internal faces of the north wall

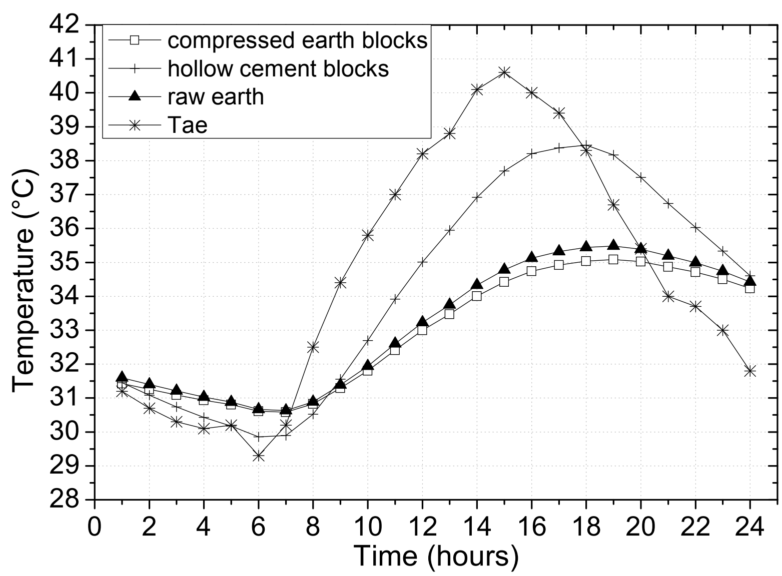

Fig. 9. Evolution of air temperatures in the interior of the house: influence of the composition of the walls

The influence of the thickness of the wall on the maximum temperatures reached within the habitat is illustrated in Fig. 10. The analysis of this figure shows that the maximum value of the temperature inside the habitat whose wall thickness is equal to 10 cm, can be reduced by 5°C when the thickness of the wall is equal to 50 cm. Thus, the temperature inside the habitat is all the more reduced in time compared to that outside, which shows that the thickness of the wall is important and contribute greatly to the reduction of air temperature peaks inside the habitat. This figure also shows that the increase in the thickness of the wall up to 25 cm generates a decrease of the maximum values of the temperatures inside the habitat (approximately 1°C for 5 cm of additional thickness). The influence of the thickness on the maximum values of the temperature is less important when the thickness of the wall is greater than 25 cm (approximately 0.5°C for every 5 cm of thickness).

The thickness of the wall reduces the maximum values of the indoor air temperature (decrement factor increasingly low) for a given rate of air change (Fig. 11). It can be seen that the increase of the ventilation also led to an increase of the decrement factor. Moreover, the increase in the thickness of the walls has the consequence of reducing decrement factor. It should be noted that over-ventilation of the habitat causes an increase in the decrement factor. Thus, it is necessary to find an arrangement between the thickness of the wall and the air exchange rate of the room to obtain an indoor air temperature of the habitat in accordance with the notion of thermal comfort. For example, for a room with an air exchange rate of approximately 2.5 vol/hour, the reduction of the thermal loads of a wall of thickness equal to 30 cm is substantially equal to that of a wall of thickness equal to 50 cm.

The time lag difference between the maximum values of the outside and inside temperatures can increase from 2 hours to 6 hours when the wall thickness increases from 10 cm to 50 cm (Fig. 12). The increase in the rate of hourly air renewal causes this time lag to fall from a certain value which depends on the thickness of the wall. For example, for a wall of small thickness (10 cm), the room can be ventilated with an air renewal rate of 1.5 vol / h for a time lag of 2 hours. For a wall of greater thickness (50 cm) the time lag difference between inside and outside is 1 hour. The effect of the ventilation decrease the time lag in the habitat, so efficiency of ventilation is partially related to the thickness of the walls of the habitat. To benefit of thermal inertia in a habitat, it's necessary to control ventilation. These results show that the more a habitat is massive, the less it needs to be ventilated.

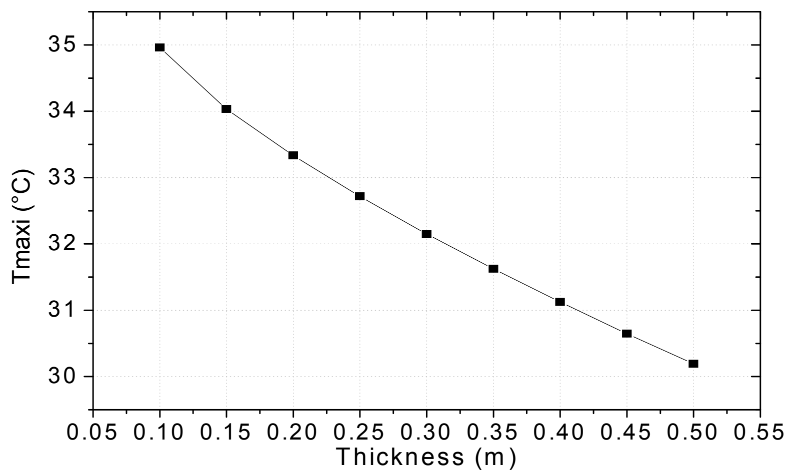

Fig. 10. Maximum temperatures reached by the indoor air of the room according to the thickness of the wall

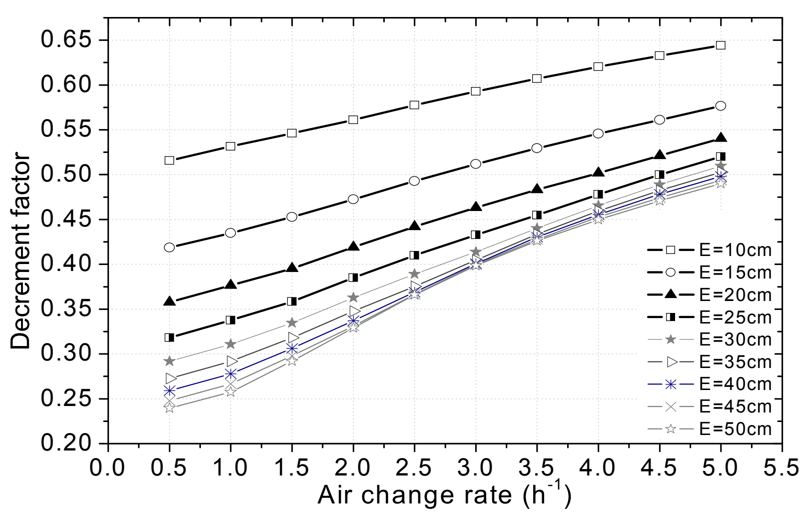

Fig. 11. Decrement factor versus air change rate: Influence of wall thickness

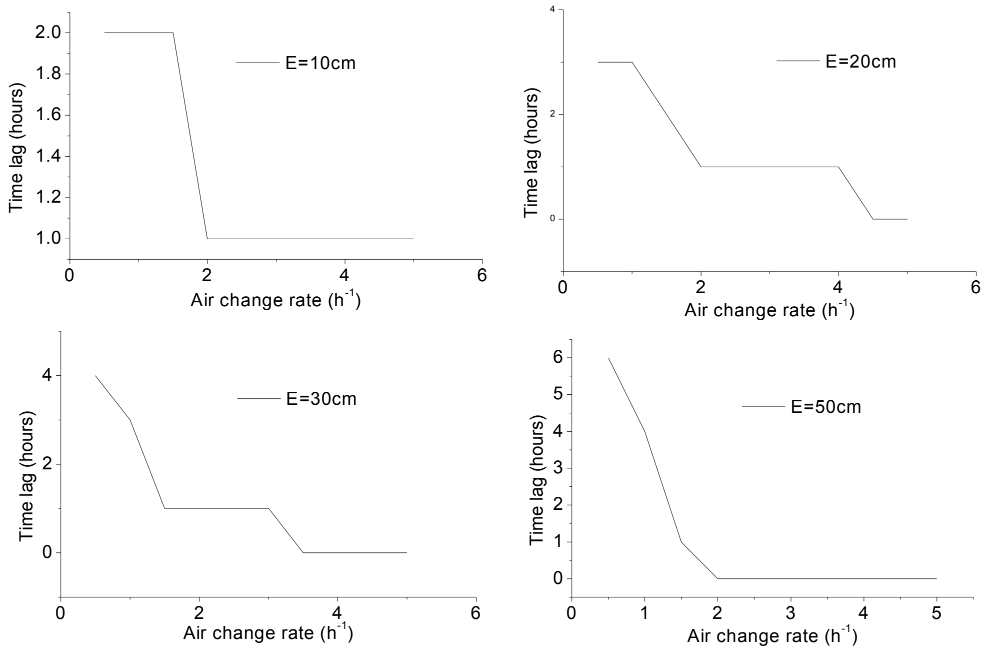

Fig. 12. Time lag according to the rate of air change: Influence of the thickness

5. CONCLUSION

We presented a numerical modeling of heat transfer in a dry tropical climate habitat (Ouagadougou city). The transfer equations based on the nodal method are solved by an implicit finite difference method and the Gauss algorithm. We analyzed the influence of the rate of air exchange, the thickness of the walls and their compositions on the spatio-temporal distributions of the indoor air temperature of the habitat and those of its walls.

It emerges from this study that:

- The raw earth and compressed earth blocks habitats offer a better indoor thermal environment than those in modern building materials (cement blocks) which is used more and more in the construction of habitats in Burkina Faso.
- The thickness of the wall plays an important role in the evolution of the maximum temperatures inside the habitat. Indeed, the increase in the thickness of the walls contributes to a better thermal inertia of the housing envelope, improves the decrement factor and the time lag difference between the inside and the outside.
- In buildings with high inertia, the rate of air exchange must be controlled because the effect of over-ventilation has a negative impact on the capacity of the habitat to reduce the maximum temperature values. This effect conducts to a considerable reduction of the time lag of the temperatures inside the habitat.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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