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A Comparative Model of Thermal Performances Between a Modern and Classic Habitat for A Hot and Humid Tropical Climate: Case of Guinea

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ABSTRACT

The objective of this research is to carry out a comparative study between a classic habitat and a modern habitat in order to understand which of the two is more efficient for a humid tropical area. To do this, a digital modeling of the heat transfer phenomena in the different components of the habitat was highlighted for a habitat made of stabilized earth bricks, a roof made of transparent tiles, false ceilings made of rectangular panels containing phase change material, concrete floor and a classic habitat made from local materials is presented. To show the reliability of this study, we validated our habitat model integrating phase change material through an experimental study carried out by researchers B. ZIVKOVIC and I. FUJII. A study on the temperature distributions at the level of certain components of the habitat done, and the influence of the variation of certain parameters was highlighted to know the thermal behavior of the two habitats. Furthermore, a comparative study was performed between the interior and exterior temperatures of the south walls of habitats incorporating PCM and without PCM, which are the components most exposed to solar radiation whose maximum values are respectively 33°C and 34, 5°C and 33.15°C against 47°C.

Keywords: Performances, thermal, bioclimatic, PCM, Tropical climate, Guinea.

INTRODUCTION

Reducing energy consumption in the building sector has become an absolute priority, the share of this sector is increasing throughout the world. Developing countries are not spared from this problem, especially since to catch up with Western countries, in particular the countries on the southern shore of the Mediterranean basin have embarked on a frantic race without taking into account the energy repercussions that their development implies [1].

Buildings are responsible for 32% of total energy consumption worldwide, including residential and commercial energy consumption of 24% and 8%, respectively. Energy consumption in buildings is increasing due to population growth, changes in human lifestyle and technological advancements. Energy consumption in buildings contributes to 30% of total greenhouse gas (GHG) emissions worldwide, while building materials account for 13% of total CO2 emissions in buildings [2]. They are responsible for global warming. The average air temperature in Europe has already increased by 1.7 °C compared to pre-industrial times [3], and the Earth's average temperature is expected to increase by 1.5 to 6°C over the next century. This global warming has already increased the frequency of heatwave periods [4] across the globe.

Heat waves worsen summer overheating by increasing the indoor air temperature of buildings [5]. Occupants spend 90% of their time inside buildings, so the quality of their indoor environment has a significant impact on their quality of life [6, 7].

Overheating buildings poses serious health risks. It caused 1,700 heat-related deaths in France and Portugal in 2022 and 167 deaths in Victoria, Australia [5]. In European countries, heating, ventilation and air conditioning (HVAC) are responsible for 20% of building energy consumption and will increase by 72% by 2030 due to climate change [3]. Cooling energy consumption is expected to increase by 223-1050% and 26-101% in Switzerland [8] and Australia [9] respectively by 2050. However, the introduction of energy-saving measures energy, including materials (low-carbon concrete [9, 10], insulation [11], phase change and retro-reflective [12]), energy-efficient and intelligent monitoring of air conditioning systems [13] and the use of renewable energy resources should reduce building energy consumption and GHG emissions [14]. For example, phase change materials (PCM) have the potential to reduce cooling energy demand by 20-50% and mitigate overheating by 4.7°C in air-conditioned and passive buildings in climates temperate and warm, respectively [15].

PCMs are latent thermal energy storage materials. They store and release thermal energy with the heat of fusion and solidification by changing phases. They can reduce and shift peak cooling demands in buildings, resulting in lower cooling costs. MCPs are used in construction with different encapsulation techniques, including active and passive modes [16]. They can be incorporated into building envelopes as structural components (tubes, pockets and panels) and construction materials (direct mixing and shape stabilization) [17]. Shape stabilization is better than direct mixing and macro-encapsulation due to its high structural integrity and absence of leakage and acidification [18]. Shape stabilization techniques have been investigated due to their simple and energy-efficient preparation procedure, low cost, better structural integrity, thermal and chemical stability, and mechanical reliability [18]. The shape-stable MCP composite (FSPCM) was used to develop thermal energy storage panels (TESPs). They have been used in buildings to reduce and shift peak cooling demand, reduce energy consumption and alleviate thermal discomfort [18].

Y. Zohir et al [19] experimentally studied a reduced-scale composite wall containing phase change materials. In this study, they found that latent heat storage actually appears very interesting in comparison with sensible heat storage. The main advantages are the storage of a large amount of heat in a reduced volume of phase change materials and the return to a temperature level close to thermal comfort temperatures.

Alvaro de Gracia et al carried out a study on phase change materials and thermal energy storage for buildings. In this study, they used the method of integrating phase change materials into clay brick supports to increase the energy efficiency of buildings. For this study, they addressed the notions of storage by sensible heat, latent heat and thermochemical reaction. Through this study, they showed that it is possible to achieve sustainable heating and cooling through thermal energy storage in buildings [20]. Lavinia Socaciu et al. [21] studied phase change materials in building construction, the study shows that incorporating suitable phase change materials into buildings can be an effective solution to reduce energy consumption and cool buildings. A small amount of phase change material can significantly increase thermal inertia without increasing the mass of the structure.

Incorporation of appropriate phase change materials into building walls, ceilings and floors can directly capture solar energy and store large amounts of thermal energy within the building envelope without the large structural mass associated with sensible heat storage, which helps to reduce the frequency of phase change phenomena, internal air temperature changes and maintain the temperature close to the desired temperature for a longer period [22].

MATERIALS AND METHODS

Materials

Presentation of the study area

Guinea is a country in West Africa, it is limited to the north by Senegal, to the northeast by Mali, to the northwest by Guinea Bissau, to the west by the Atlantic Ocean, to the south by Sierra Leone and Liberia, to the east by Ivory Coast and part of Mali. It has an area of 245,857 km^2 [23].

The climate is divided into two zones: tropical and subequatorial. The four regions have their own meteorological characteristics due to the diversity of the relief. The tropical climate is itself divided into:

- Tropical maritime climate in Lower Guinea;
- Tropical mountain climate in Middle Guinea;
- Dry tropical or Sub-Sudanian climate in Upper Guinea;
- Subequatorial climate in Forest Guinea.

The climate map of Guinea is shown in Figure 1.

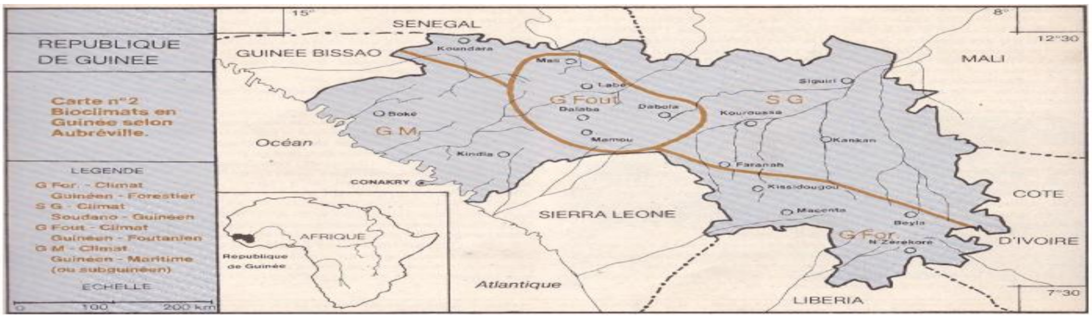

Fig. 1 Climate Map of Guinea [23]

Climatic data

The tools we used for this research are the meteorological data for the typical April day of the Guinea region shown in Figure 1, which represents the most critical month of this region during the 12 typical days. The programming language is FORTRAN for simulation and Origin software for drawing curves.

We therefore select the climate data for the typical April day as input to our program because they allow us to analyze the thermal behavior of the habitat for extreme weather conditions.

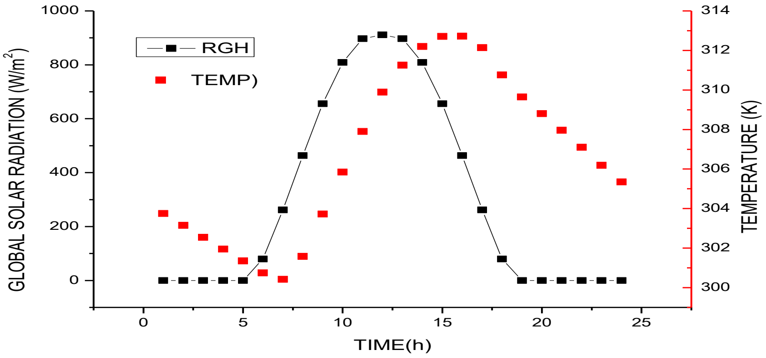

Fig. 2 Global solar radiation and ambient temperature of the Guinea region

Physical model of bioclimatic habitat

The bioclimatic roof model we use for this study is a flat solar collector whose cover is made of transparent tiles. We consider, as shown in Figures 3 and 4, a bioclimatic type of habitat that can be broken down into a roof and a parallelepiped section enclosure separated by a rectangular panel containing phase-change materials encapsulated as false ceiling. The roof consists of an inclined transparent tile slab at an angle of 30 ° to the horizontal consisting of a panel of phase change material and the vertical walls of stabilized earth bricks in which air circulates through convection. The thermophysical properties of the materials constituting the roof, the false ceiling and the parallelepiped enclosure, assumed to be constant are reported in Table 1.

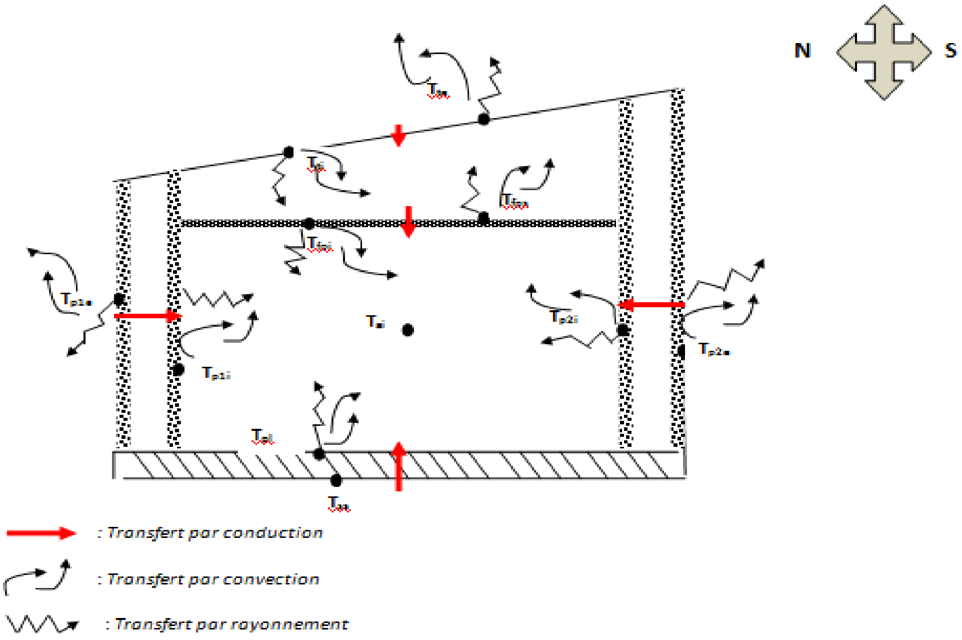

Fig 3: Model of habitat

Table 1: Thermophysical properties of materials [19, 20, 21, 22]

Materials	Density ρ (kg/m^3)	Heat capacity Cp (J/Kg/K)	Thermal conductivity K (W.m^{-1}.K^{-1})
Transparent tiles	1200	800	0.752
BTS	2000	1500	1.1
Hydrated salt	1710	1400	1.09
Paraffin RT27	870	2400	0.24

Mathematical formulation of the model

Simplifying assumptions

The methodology adopted for describing the thermal behavior of our habitat model is based on nodal analysis [21].

The detailed study of the heat transmission phenomena involved in the functioning of the habitat (figures 3 and 4) leads us to make a number of hypotheses, the main ones being:

- The heat transfers are unidirectional, perpendicular to the walls;
- The thermal inertia of the air is neglected;
- The materials are assimilated to gray bodies;
- Convective heat transfer between the top wall of the PCM and the indoor air of the roof is neglected;
- The upper wall of the pcm receives a quantity of imposed solar flux;
- The mode of heat transfer in the PCM is purely conductive.

Basic equations

The establishment of transfer equations is based on the analogy between thermal and electrical transfers.

In a general way, the instantaneous variation of the energy within a component of the habitat is equal to the algebraic sum of the flux densities exchanged within this component.

This is written:

$$\frac{M_i\,Cp_i}{s}\frac{\partial T_i}{\partial t}=DFSA_i+\sum_{i=1}^{n}\sum\nolimits_x \varphi_{xij} \tag{1}$$

$\varphi_{x_{ij}}$: Heat flux density exchanged by the transfer mode x (conduction, convection and radiation) between the media (i) and (j), ($W.m^{-2}$)

S: Wall section (m^2)

$DFSA_i$: solar flux density absorbed by the material (i) ($W.m^{-2}$) $DFSA_i=\alpha_i\,\varphi_i$ (2)

α_i : Thermal absorption coefficient of the material (i)

φ_i : Solar flux density captured by the surface of the medium (i) ($W.m^{-2}$).

By introducing an exchange coefficient $h_{x_{ij}}$ and by linearizing transfers, we can write:

$$\varphi_{xij}=h_{xij}\left(T_j-T_i\right) \tag{3}$$

Thus, the equation 1 is written:

$$\frac{M_i\,Cp_i}{s}\frac{\partial T_i}{\partial t}=DFSA_i+\sum_{i=1}^{n}\sum\nolimits_x h_{xij}\left(T_j-T_i\right) \tag{4}$$

We will then apply Equation 3 to the various medium of our system.

Internal wall of building

$$\frac{M_{pi}\,Cp_{pi}}{s}\frac{\partial T_{pi}}{\partial t}=\frac{K_{pi}}{Ep_{pi}}\left(T_{pe}-T_{pi}\right)+hc_i\left(T_{airh}-T_{pi}\right)+\sum_{i=1}^{n}hr_{i\rightarrow pi}F_i\left(T_i-T_{pi}\right) \tag{5}$$

Building air zone

$$\frac{M_{air}\,Cp_{air}}{s}\frac{\partial T_{airh}}{\partial t}=\sum_{i=1}^{n}h_{ci,pi}\left(T_{pi}-T_{airh}\right)+\phi_{ra} \tag{6}$$

Exterior wall of building

$$\frac{M_{pex}\,Cp_{pex}}{s}\frac{\partial T_{pex}}{\partial t}=\alpha_{pex}\varphi_{pex}+\frac{K_{pex}}{Ep_{pex}}\left(T_{pi}-T_{pex}\right)+hc_{ex}\left(T_{amb}-T_{pex}\right)+hr_{vc,pex}\left(T_{vc}-T_{pex}\right)+hr_{sol,pex}F_{sol}\left(T_{sol}-T_{pex}\right) \tag{7}$$

Air renewal

Considering a volume of air V exchanged between the outside and the inside of the habitat, this corresponds to a quantity of heat Q in joules. By supposing that volume is exchanged every hour. We will thus have an air exchange flux Φ_{ra} ($J.h^{-1}$):

$$\phi_{ra}=c\,\dot{Q}\left(T_{airout}-T_{airins}\right) \tag{8}$$

With:

$\dot{Q}$ the volumic flow rate in $m^3.h^{-1}$;

c the heat of the air ($c=1225J.m^{-3}.K^{-1}$);

T_{airout} ambient air temperature outside the home;

T_{airins} air temperature inside the enclosure of the building.

Equation of heat in the phase change material

Continuity of flux at the solid-liquid interface, by posing that the difference between the flux on either side of the interface is equal to the amount of instantaneous heat released or absorbed in the form of change-phase heat.

Sensible phase

$$\text{If } T\le T_F \quad \frac{\partial T}{\partial t}=\left(\frac{\lambda}{\rho Cp}\right)_s\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}\right) \tag{9}$$

$$H_{i,j}=\rho_s Cp_s\left(T_{i,j}-T_{amb}\right) \tag{10}$$

Latent Phase

$$\text{If } T \succ T_F \text{ and } H_{i,j} \succ \rho_s Cp_s \left(T_F - T_{amb}\right) \qquad (11)$$

$$\frac{\partial H}{\partial t} = \lambda_s \left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} \right) \qquad (12)$$

$$H_{i,j}^{t+\Delta t} = \lambda_s \left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} \right) \Delta t + H_{i,j}^{t} \qquad (13)$$

Sensible phase

$$\text{If } H_{i,j} \succ \rho_s Cp_s \left(T_F - T_{amb}\right) \qquad (14)$$

$$\frac{\partial T}{\partial t} = \left(\frac{\lambda}{\rho Cp} \right)_s \left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} \right) \qquad (15)$$

$$H_{i,j}^{t+\Delta t} = H_{i,j}^{t} + \rho_l Cp_l \left(T_F - T_{i,j}\right) \qquad (16)$$

Boundary conditions

Boundary conditions are defined along both axis X and Y.

Following the Y axis, we have:

$$\alpha\left(T_{air} - T_{pcm}\right) = \lambda \left(\frac{\partial T}{\partial X} \right)_{pcm} \qquad (17)$$

Following the X axis, we have:

$$\alpha\left(T_{air} - T_{pcm}\right) = \lambda \left(\frac{\partial T}{\partial Y} \right)_{pcm} \qquad (18)$$

Methods

For the resolution of the equations in the habitat and in the storage unit of the phase-change material, we have applied respectively the Gauss and Thomas algorithms all coupled to an iterative method for solving the equations and the two algorithms are coupled by a notion of average temperature. The systems of algebraic equations obtained by establishing energy balances on the different components of the habitat model are of the form [23]:

$$C \frac{dT(t)}{dt} = -K.T(t) + B.\Phi(t) \qquad (19)$$

With:

$T(t)$: Vector of temperatures at different time-dependent nodes t;

C : Vector column consisting of thermal capacities at different nodes;

K : Square matrix composed of thermal conductance;

B : Matrix coefficient for the different nodes;

$\Phi(t)$: Vector column representing the inputs of the system (thermal excitations).

Equations (v to vii) are discretized by an implicit finite difference method whose resolution requires iterative computation. The system is solved by the Gauss algorithm coupled to an iterative method because the transfer coefficients depend on the temperatures of the different components of the habitat. The enthalpic method is applied for the resolution of the heat equation, it is known by its robustness and results from the fact that it makes it possible to determine the temperature field without having recourse to the knowledge of the progression of the front of solidification in the time. It thus makes it possible to solve phase change problems for complex geometries but also when there is a pasty zone. The principle of this method is that for both phases, a single variable, enthalpy H, is used as an unknown and thus reduces the equation system to a single heat transport equation (9-18). For this method, generally, the reference temperature is equal to the phase change temperature (melting temperature). This heat equation is solved by Thomas's algorithm.

RESULTS AND DISCUSSION

Model validation

Many model validation methods exist, for our case we validated our model with the experimental study carried out by [19] who carried out an experimental study of heat transfer in a parallelepiped-shaped tank filled with PCM (Salt Moisturized) and soaked in a water tank at a temperature of 60 ° C. The walls of this tank are made of stainless steel (100x100x20 mm) and thermally insulated (adiabatic process). The temperature in the middle of the PCM is measured using a K-type thermocouple placed in the center of the tank. The curve in Figure 6 allows us to assert that there is indeed a close qualitative and quantitative relationship between our numerical simulation and the chosen experimental model. The fusion time of our numerical model is long compared to the experimental model, this is due to the fact that the phenomenon of convective heat transfer at the level of the PCM is neglected in the numerical model.

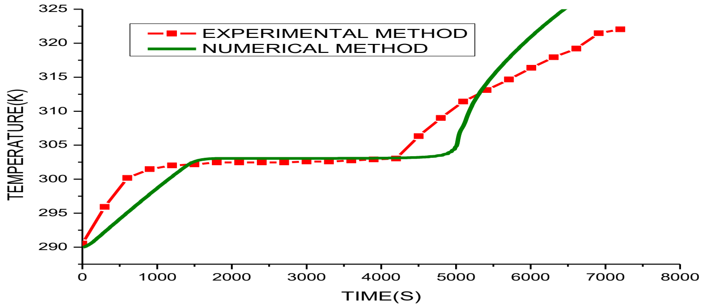

Fig. 4 Model validation

Temperature distribution in habitat components

We present in Figure 5 the evolution of the air temperature in the enclosure of the habitat without phase-change material (classical habitat) and with a habitat integrating phase-change material (modern habitat) for the typical day of the month of April. According to this figure, we find that the air temperature in modern habitat decreases compared to conventional habitat because the PCM stores heat during the day and restites it during the night when the building is cooled down by the effect of the celestial vault, while in the classical habitat, this heat penetrates inside the habitat and the indoor air is overheated and the temperature increases. The maximum temperatures observed in conventional and modern habitat are 34.8 ° C and 33.5 ° C, respectively.

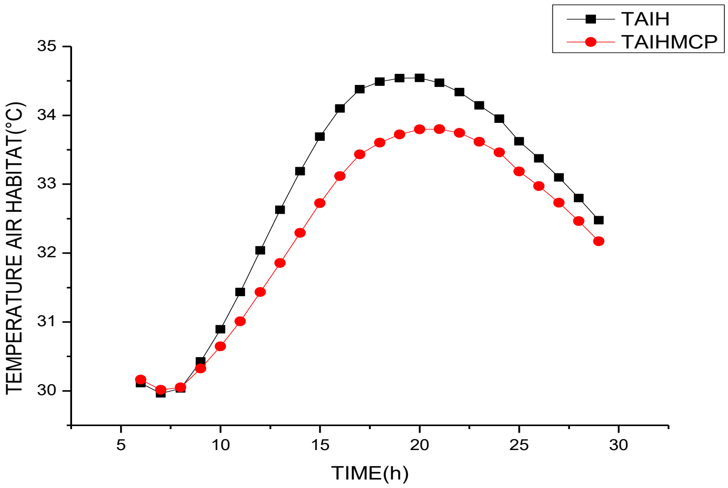

Fig. 5 Indoor air temperature of habitat with and without PCM for the month of April

Figure 6 illustrates the indoor south wall temperature profile for habitat with and without PCM for the typical April day. We find that the interior temperatures of the south wall of CWD-free habitat dominate those of the PCM-integrating habitat from 10:00 am to 5:00 am. This demonstrates that the integration of PCM in the habitat brings a significant thermal inertia compared to the habitat without PCM and contributes to the improvement of the thermal comfort of the living space of the habitat.

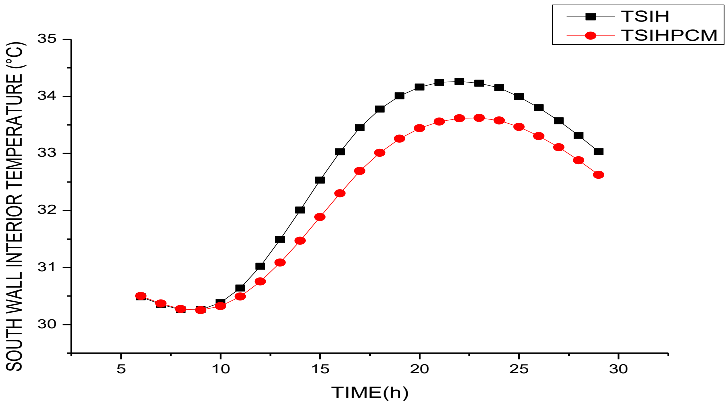

Fig. 6 Southern interior wall temperature of habitat with and without PCM for the month of April

Influence of certain parameters on the temperature distribution

Figure 7 shows the influence of variation in wall thickness on the temperature of the interior south wall of the habitat with and without PCM. We note that with a greater thickness of the wall of a habitat, the greater thermal inertia is important, and the heat propagation from the outer south wall to the inner south wall is dampened. For thermores the effect of the exchange of heat by convection between this wall and the air of the enclosure plays an important role, which implies the lower temperature of the southern interior wall of the habitat. By comparing the temperature profiles of the two walls, we find that the temperatures of the internal faces of the south wall of the habitat integrating PCM decrease compared to the habitat without PCM.

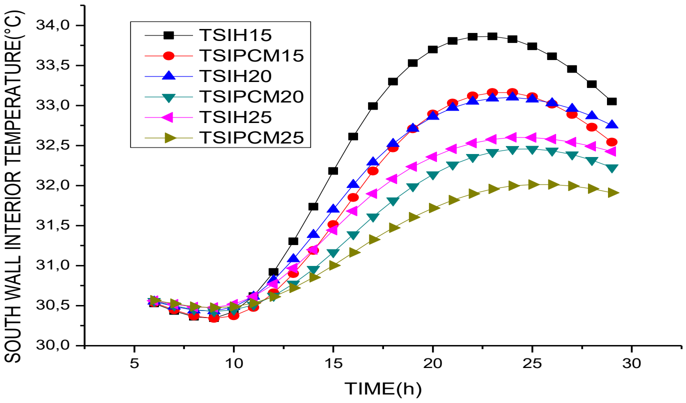

Fig. 7 Influence of Wall Thickness Variation on Interior South Wall Temperature with and without PCM

Figure 8 shows the influence of air change rate variation on air temperature in the enclosure of a habitat with and without PCM. In this figure, we find that the higher the value of the renewal rate, the higher the value of the air temperature increases in the enclosure of the habitat. By comparing the two habitats, we find that temperatures increase in the enclosure of the habitat without PCM compared to the habitat integrating PCM. This is due to the exchange of warm air from the outside to the interior of the habitat during the day, and towards the evening there is the convection phenomenon between the walls and the indoor air and the radiation between the walls and the sky that cause the decrease of the temperatures. Although the variation of the air change rate influences the temperature of the air in the enclosure of the habitat, we observe on this figure that the temperatures of the air fall in the habitat with PCM compared to a habitat without PCM.

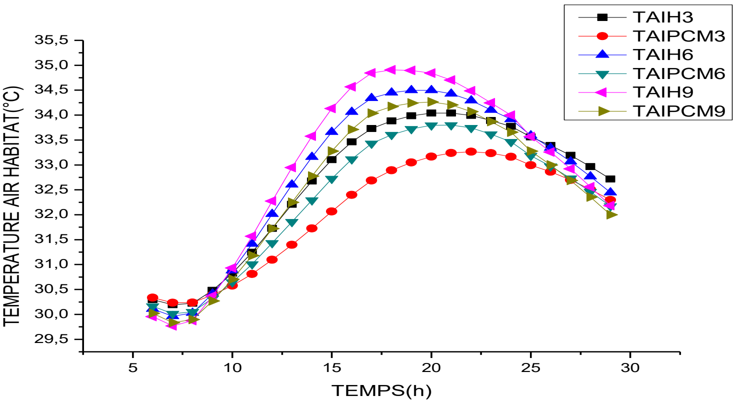

Fig. 8 Influence of air change rate on indoor air temperature with and without PCM

Figure 9 shows the influence of variation in wall thickness on air temperature in the habitat enclosure with and without PCM. We find for a greater thickness of the wall of a habitat, the thermal inertia is greater and the temperature of the indoor air of the habitat is lower, this is due to the fact that the heat propagation in the wall is slowed and the effect of convective exchange between interior walls and indoor air also plays an important role. By comparing the temperature profiles of the two habitats, we observe that the air temperature drops considerably in the habitat integrating PCM compared to habitat without PCM.

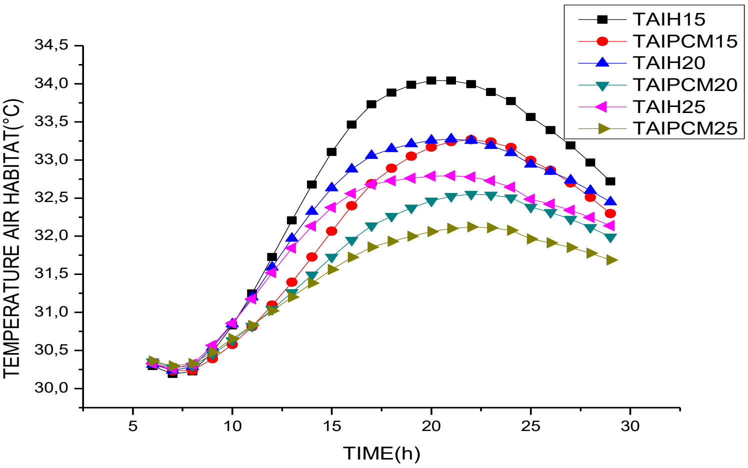

Fig. 9 Influence of variation of wall thickness on indoor air temperature with and without PCM

CONCLUSION

We presented a numerical modeling of heat transfer within the two habitats, namely: a classic habitat and a modern habitat. This numerical modeling was validated using an experimental model proposed by researchers ZIVKOVIC and FUJII. Thus, we analyzed the influence of certain parameters on the thermal behavior of the habitat through meteorological data from the Republic of Guinea (solar flux and ambient temperature) for the typical day of the month of April which is one of the warmest months in this region. For better efficiency of our study, we compared the air temperature in the enclosure and the temperatures of certain interior walls for a habitat incorporating phase change material (modern habitat) and a habitat without phase change material (classic habitat). This allowed us to demonstrate that a home incorporating a phase change material provides much more comfort in the living space of a home compared to a home without a phase change material (classic home).

Declaration by Authors

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