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Numerical Investigation of the Effects of Insulated Envelopes on Hygrothermal Comfort within Habitats of Southern Benin: Test of a Local Material

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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Short Research Article

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ABSTRACT

Aims: The objective of this work was to investigate the effect of the thermal insulation with polystyrene or local straw on the indoor comfort (time evolution of temperature and hygrometry, variation of thermal load). The study aimed also to determine the optimal thickness of the insulators, and to check the contribution of a controlled mechanical ventilation (CMV) to reach a better indoor comfort in humid tropical climates, along with ecological and low cost criteria.
Methodology: The studies were conducted on a typical residential building in Benin located in Cotonou with the following geographic coordinates: Latitude 6°38 'North, Longitude 2°34' East. Dynamic thermal simulation series were conducted to analyse the thermal behaviour of the sample building. Mainly two insulators were examined: a manufactured one (polystyrene) and a local material (straw). The TRNSYS software was used to model the building and to realize the different simulations.

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Results: The study showed that the thermal insulation by the inside of the walls and ceiling with polystyrene reduced on average the cooling requirement of 4°C. But an average increase of 25% was observed on the relative humidity. In the same way the complete insulation with straw keeps the average indoor temperature at 27°C which is higher than that of polystyrene (24°C), but humidity with straw was lower for the same average insulation thickness. Moreover, the ecological footprints of manufactured insulation such as polystyrene are higher than those of natural products as straws. The integration of the CMV has ensured good indoor air and correct humidity control between 67% and 76%. These values are in line with the regulatory values in Benin.

Conclusion: the study outlined the need to insulate building even in tropical areas in order to reduce the energy consumption linked with air conditioning. Moreover it promotes the use of natural insulators as straw to improve carbon footprint of buildings in Benin. With a good building envelope insulation coupled with an appropriate ventilation, the need of artificial air conditioning becomes weak, and may even be unnecessary in some cases.

Keywords: Thermal comfort; thermal insulation; cooling requirements; humidity control; dynamic thermal simulation; ventilation.

1. INTRODUCTION

The building sector is the world's largest energy consumer, Chenailler [1]. Lifestyle changes lead humans to spend more time indoors at home, school, offices, transportation, stores, etc. Otherwise, in Benin the population is growing noticeably, rising from 6,769,914 inhabitants in 2002 to 10,008,749 inhabitants [2], according to the latest census achieved in 2013. As a result, the demand for housing is increasing dramatically. This makes construction one of the main engines for economic growth in the country. This increase induces a high demand for electrical energy. In addition, the production of local electrical energy is only between 10 and 30% of the total supply for the country [3]. As Benin is a country with a hot and humid tropical climate in the South, the thermal comfort in buildings is supplied mainly by the use of air conditioning. These problems lead to high energy consumption, mostly of fossil origin. But fossil fuels are exhaustible and their combustion to produce electrical energy generally generates greenhouse gases. The energy bill is important, moreover, the high cost of air conditioning equipment and maintenance are also a real financial challenge for consumers in developing countries.

The current construction of the habitats and offices in Benin takes into account neither the thermal insulation of the walls nor the controlled mechanical ventilation (CMV), even if the insulation of buildings is known elsewhere as an effective way to reduce the energy requirements for heating and cooling while improving comfort. Moreover, the reduction of energy consumption leads implicitly to the reduction of greenhouse gas emissions. The inhabitants and their activities in the service rooms (kitchens, bathroom, laundry ... etc.), as well as the operation of some appliances eject moisture and pollutants. This drives to the degradation of the building and may cause important impacts on the health of the inhabitants. Thus, it is important to provide fresh air with adequate ventilation, such as CMV, to improve the indoor air quality by ensuring automatically the supply of regulated spelling airflows.

2. LITERATURE REVIEW

In order to better control the energy consumption in the housings, to preserve the materials from the attacks of humidity, to ensure the hygienic conditions for the health and to have a good comfort, several authors worked on the improvement of the thermal comfort and insulation, the ventilation and the energy performance in buildings. Thus, Cetiner et al. [4] have investigated wood waste as an alternative thermal insulation solution for buildings. It emerged from the study that the thermal conductivity values of wood waste of different densities are between 0.048 and 0.055 W/mK. These values are slightly higher than those of commonly used non-organic insulation materials, although there are of the same order of magnitude as the conductivities of other natural insulation materials available on the market. Wood waste insulators have the inherent advantage to be ecological and cost-saving. The use of bio-sourced materials has proven to be a quiet good solution to improve the energy performance of buildings. In a recent work, Hounkpatin et al. [5] have shown the impact of the use of natural local and manufactured roofing materials on the hygrothermal comfort of habitats in humid tropical environments. It has been noticed that straw has a positive impact on the overall thermal and environmental performance of buildings. The straw reduces the need for cooling by 37%, compared to 15% for the terracotta roof and showed a 40% increase for a zinc sheet roof compared to a standard slab roof. Gédéon et al. [6] suggested that the most recommended measures for the operation of air-conditioning equipment are those that favour an ambient temperature of around 24°C. These measures applied to buildings enabled them to reduce energy consumption by around 38% to 45%. The indoor thermal environment is strongly influenced by the local climate, and air circulation through the building is necessary to reduce indoor discomfort due to overheating conditions in a tropical climate [7]. Other authors have been investigated the characteristics of building envelopes. In this approach, Fezzioui et al. [8] studied the influence of the building envelope on the energy demand. Their work focused on two types of buildings with different climatic conditions, namely the city of Béchar and the city of Tamanrasset. The simulations were implemented with TRNSYS software; they deduced that increased inertia of the exterior walls, roof insulation and window surfaces improve the thermal comfort. Sobhy et al. [9] working on the same thematic, have investigated the effect of the roof insulation and the facades on the cooling requirement of a villa type house located in Marrakech, by the means of thermal simulations using also TRNSYS software. The results revealed that roof insulation in Marrakech's climate can provide a diminish of the cooling requirements up to 40%. In addition, the insulation of the facades by an air gap reduces this load by almost 15%. Aktacir et al. [10] studied the effect of insulation on a simple building in Adana, Turkey (Mediterranean climate). They have shown that increasing the thicknesses of expanded polystyrene results in a reduction in cooling energy requirements. Guechchati et al. [11] treated the same case, where the insulation of the roof coupled to the external insulation of the walls with 6 cm of expanded polystyrene was retained as an optimal solution. Martineza [12] examined the highly insulated systems for energy renovation of facades to improve room comfort; he pointed out that metal profiles systems should not be placed within the layer of insulation, because the overall heat transfer is increased by almost 40%; the problem was elucidated by incorporating nonmetallic plastic composite profiles.

Elsewhere, Kaboré [13] has shown that the use of optimized windows results in a reduction of almost 22% in the cooling capacity necessary for the air-conditioned building and a reduction of around 5% in the period of discomfort, if air conditioning is not available. Other aspects are closely linked to the reduction of energy consumption in buildings; some of them are the activities of the occupants, and the ventilation. Several authors have addressed this issue ([14]-[24]). The ventilation of the premises is one of the parameters to improve the indoor environmental conditions and to restore better hygienic conditions and comfort in dwellings in Benin ([25]). The present work deals with the effect of the insulation of the whole envelope (walls and roof) on the hygrothermal comfort of a villa in Cotonou. The thermal insulators tested in the simulations are polystyrene and straw. Another particularity of the work lies in the optimization of the insulation on the whole building, as well as the integration of the CMV, contrary to the aforementioned works on thermal insulations in tropical environments.

3. MATERIALS AND METHODS

3.1 Materials

This work consists in studying the effect of the thermal insulation of the envelope on the energetic performances of the building and in evaluating the influence of the simple flux CMV on the thermal comfort. The thermal insulation of the building envelope is one of the most effective ways to improve thermal comfort with less energy consumption. In a temperate environment, thermal insulation of building envelopes decreases gains during the summer and heat losses during winter season ([26]). The purpose of the Controlled Mechanical Ventilation system is to maintain good indoor air quality inside buildings. This system makes it possible to ensure an independence of the air exchange rate with respect to the external conditions. It is widely used in new homes ([27]). For the case study, a representative residential building was chosen regarding the building materials and construction methods in the southern zone of Benin. This quantitative study is based on the dynamic thermal simulation of the building using the software TRNSYS 17 during the hottest month of the year (March), considering a time step of 1 hour. As input to the software, the geometric and thermo-physical description of the house were completed using the sketch of the house. The weather data of the city of Cotonou were also supplied. To ensure the comfort of the occupants, the following temperature and relative humidity guidelines are recommended by the building code in Benin (Table 1).

The psychrometric diagram (Fig.1) shows the comfort zone in Southern Benin.

3.1.1 Layout and characteristics of the basic building

The identified building, support of the study, is an accommodation including a living-room, two bedrooms, a bathroom and a kitchen. It is a typical house (without insulation) of the urban social class in Benin. A plan view of the building is displayed in Fig. 2.

The multizone design of the geometry of the residential building was created using the Google SketchUp software to which the add-on Trnsys3d has been associated. While creating the geometric model, the six climatic zones of the building were first constituted (Table 2), then the doors and windows followed, and finally the surfaces were linked in order to establish a thermal connection between the various adjacent parts (Fig. 3). The equations governing the energy balance in the building are not displayed here, as they have been already developed elsewhere by the authors [5].

3.1.2 Composition and materials of the walls

The composition and the thermo-physical characteristics of the walls constituting the basic building envelope are given in Table 3.

Table 1. Comfort zone in Southern Benin [3]

Dry bulb temperature (°C)	Relative humidity (%)	Dry temperature range (°C)	Relative humidity range (%)
24,5	65	24 à 27	30 à 70

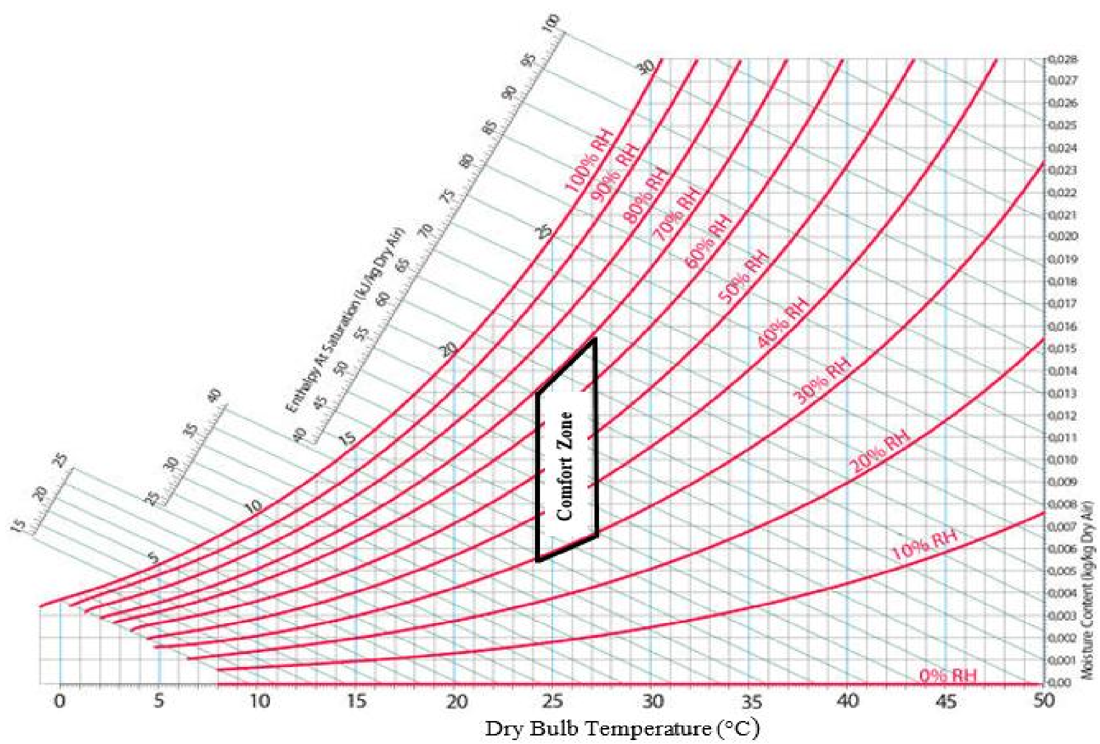

Fig. 1. Comfort zone in Southern Benin

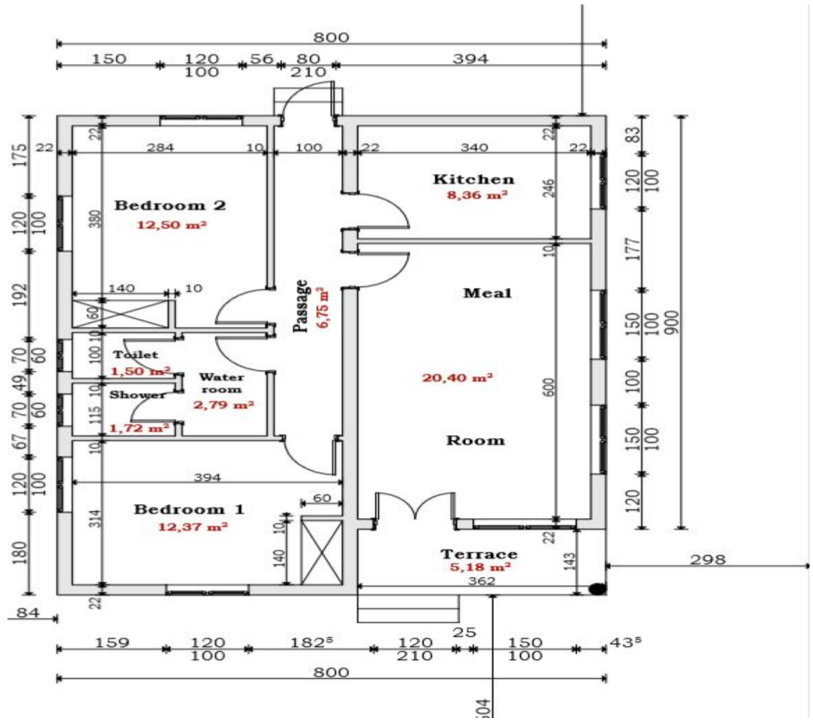

Fig. 2. Plan view of the studied building

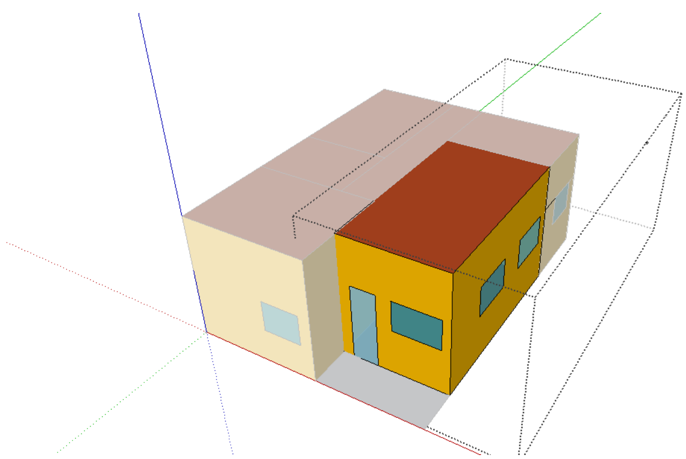

Fig. 3. 3D construction of building zones under Google Sketchup

Table 2. Climatic zones of the building

Zones	Height (m)	Surface (m²)
Living-room	4	95,6
Room 1	4	69,01
Room 2	4	52,47
Kitchen	4	50,15
Bath room/WC	4	47,11
Hallway	4	26,6

To ensure a lower transmission coefficient, double glazed windows were chosen. Each of them is composed of two walls of 4mm glass and an air gap of 12mm thick, thus presenting an overall transfer coefficient U of 2.8W/m^{2}K and a glazing insulation factor g of 0.75 [29].

3.1.3 Insulation of the envelope

Insulation is added to the walls and roof of the initial basic building to investigate its impact on the thermal comfort. In the study, the insulation is provided from inside (see the ANNEX). Two thermal insulators are studied: The French

ACERMI institution certificated extruded polystyrene and local straw bale, respectively. Insulators are used in several thicknesses: 3 cm, 5 cm, 10 cm and 15 cm. The evolution of the internal temperature, the relative humidity and the cooling requirement of each zone of the building are computed. The optimum thickness is also checked. The needed thermal characteristics of insulators are shown in Table 4 [31].

3.2 Methods

3.2.1 Strategy of occupancy

The assumption is made that the house is occupied by a family of 4 people: a man, a woman, and two teenagers. The level of metabolic activity is 1met (3.5 mlO_2 /kg/min), the thermal resistance of clothing is equal to 0.5Clo (1clo = 0.155 $K \cdot m^2 \cdot W^{-1}$), and the relative air speed equals to 0.1m/s. Two occupancy scenarios are defined on working days and weekends (Fig. 4). Bedroom 1 is occupied by parents, and bedroom 2 by children. It can be noticed that more occupants are staying at 7am and 9 pm on weekdays (Fig. 4a), but at the weekends, the maximum occupation occurs during lunch (14h) and dinner (21h) (Fig. 4b). From 0h to 6h the whole family is asleep.

3.2.2 Occupancy moisture production scenario

Table 5 shows the water production of each occupant according to age and activity (awake or asleep) Koffi [30].

Table 3. Thermo physical properties of the materials ([13], [28])

Envelope of the building	Composition of the envelope	Width (m)	Thermal conductivity (W/mK)	Heat capacity (J/kg.K)	Density (kg/m^3)
Wall	Exterior cement Plaster	0.02	1.15	1000	1700
	Hollow brick	0.15	0.833	1000	1000
	Interior cement plaster	0.02	1.15	1000	1700
Floor	Tile	0.008	1.15	700	1800
	Mortar laying tiles	0.02	0.87	1001	2200
	Concrete	0.2	1.4	1001	2200
Roof	Exterior cement plaster	0.02	1.15	1000	1700
	Concrete slabs	0.2	1.4	1001	2200
	Air blade	0.9	0.08	1227	1000
	Plywood	0.012	0.32	801	790

a

b

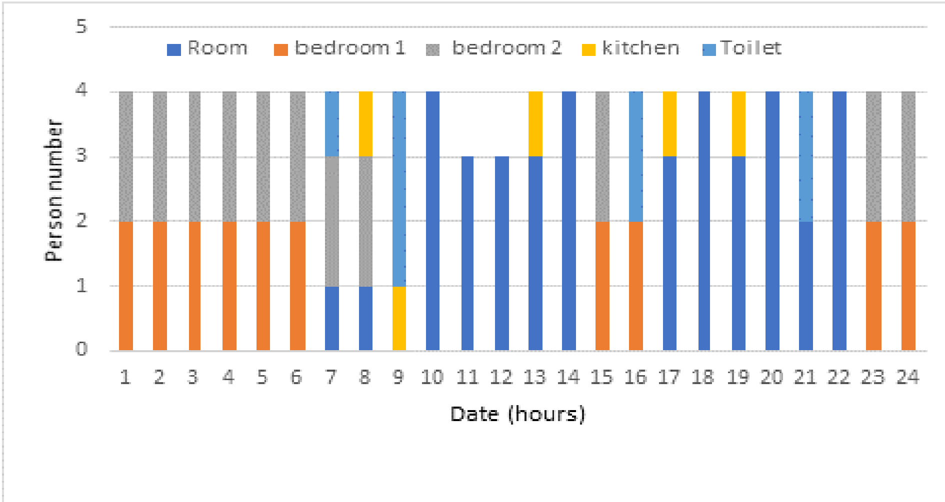

Fig. 4. Occupancy scenario of the different zones: (a) Occupancy profile for working days, (b) Occupancy profile during weekends

Table 4. Thermo physical properties of the used inside insulators

Insulators	Thermal conductivity (W/mK)	Specific heat (J/kg.K)	Density (Kg/m^3)	Cost (XOF/m^3)
Extruded Polystyrene	0.028	1000	25	85 000
Straw	0.07	1700	100	8 500

Table 5. Production of water according to age and activity

Occupant	Activity	Produced humidity (g/h/pers)
Older than 15 years	Awake	55
	Asleep	30
Age between 10 and 15 years	Awake	45
	Asleep	15

The production of humidity for each shower is evaluated to 300 g/person. In the kitchen, it is 50g for breakfast, 150 g for lunch and 300g for dinner.

3.2.3 Scenario of the use of household appliances

Uses are often related to the presence of humans and their activities. The values usually taken into account are displayed in Table 6.

Fig. 5 shows the lighting scenarios for the different main rooms and services. From 18h, lamps are lit on, according to the scenarios.

Table 6. Power consumed by household appliances

Appliance	Zone	Time of use (h)	Power (W)
Television	Living room	9 -11 & 20- 24	65
Refrigerator	Kitchen	24/day	100
Computer	Room 1	20- 24	230
Home cinema	Living room	9 -11 & 20- 24	300
Radio	Room 1	6-7	10

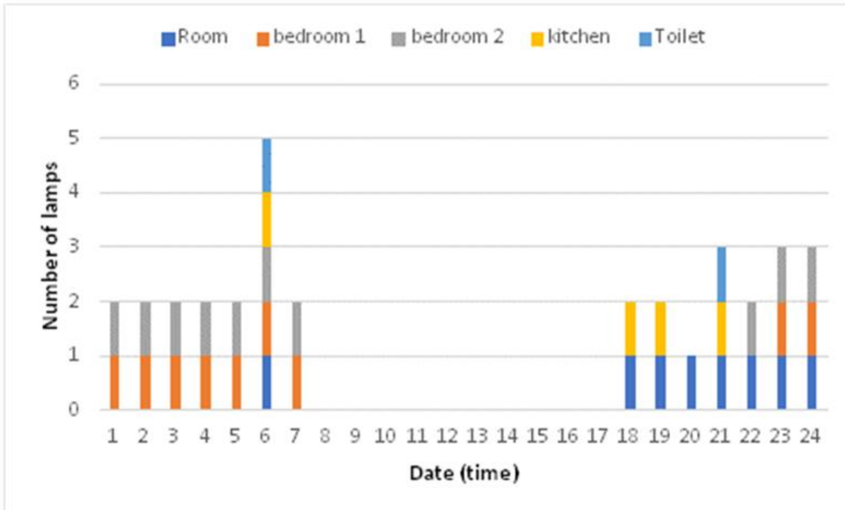

Fig. 5. Lighting scenario of the different zones (artificial lighting 10W/m²)

Table 7. Air Renewal rates through air intake modules of windows

	Module of air intake	Number of modules	Flow rate Q_{EA} (m^3/h)
Living rom	30	2	2x30=60
Bedroom 1	22	1	22
Bedroom 2	22	1	22
Total			104

Q_{EA} represents the fresh air rate through the modules.

3.2.4 Renewal of air in the building

The work carried out in this part takes into account the renewal of air by the windows at first, and in a second time by the CMV. In the first case, the windows are supposed open with an infiltration rate of 0.9 vol/h [29]. But in the second part, the renewal of infiltration air is achieved through the self-adjustable modules of the air inlet in the living room and bedrooms even though the windows remain closed, thanks to openings in the joinery to which are mounted modules. The modules are installed at the top of the windows in both bedrooms and the living room. It is recommended to install at least 2 air inlets modules (22, 30 or 45) in the living room and at least 1 air inlet module (22 or 30) per bedroom [32]. The number after the module (22, 30 or 45) refers to the rates of infiltration air flow in m^3/h. Table 7 shows the dimensions and rates of air exchange through the air intake modules for this study.

For proper operation, the previous modules must be coupled with an air extraction. The single flow CMV system considered here has self-adjusting extraction vents in service rooms (in the toilet and the kitchen) and self-adjusting air inlet modules (in the living room and bedrooms). These entrances ensure the admission of fresh air into the main rooms, and this air then flows through the dwelling; in doing so, it carries the internal pollutions and becomes stale. Extraction fan pulls stale air from damp rooms (kitchen, bathroom/WC) through extraction vents and exhausts the polluted air outside. The maximum flow rate extracted ($Q_{max\ extract}$) has to be less or equal to the sum of fresh air intake rate through the installed modules added to the leakage due to the permeability of the housing [32]:

$$Q_{max\,extract} \leq \sum (Q_{EA} + Q_{leakage})$$

Here, Q_{EA} is determined according to table 7, whereas $Q_{leakage}$ is chosen using experimental data [32]. For such a housing, $Q_{leakage}$ is estimated to $60 m^3/h$. The calculation of the extracted air rates is summarized in Table 8.

$$Q_{max\,extract} = 150\ m^3/h\ ,\ \sum Q_{EA} = 104\ m^3/h$$

The choice of air inlets is therefore correct. Indeed, the sum of the air inlet modules and leakage (164 m^3/h) is greater than $Q_{max\ extract}$.

Table 8. Airflow from extraction vents

	Airflow from extraction vents (m^3/h)			
Number of rooms	**Kitchen**	**Bathroom**	**WC**	**Total**
3	105	30	15	150

4. RESULTS AND DISCUSSION

The study was first deployed on a standard reference building in the region to which the interior insulation is integrated as an alternative. Air infiltration rates was also taken into account. The external conditions considered for the simulations are those of March, the hottest month of the year. Thus, the following presentations are available:

- On the same graph (Figs. 6 or 7), the change in relative humidity and temperatures in the main rooms (living room, bedroom 1, bedroom 2) and service rooms (kitchen, shower) on the reference building.
- On the same graph (Fig. 9), the cooling needs of the main parts and the service rooms.
- It was also developed afterwards:
- The effect of envelope insulation on thermal comfort
- The optimization of the polystyrene thickness
- And finally the effect of controlled mechanical ventilation (CMV) on the inside environment.

4.1 Presentation of the External Climatic Conditions

For a period of one month, Fig.6 describes the hourly variations of the external humidity and temperature. The outside temperature varies between 22°C and 34°C during the month of March. The lowest values are observed in the night between 1am and 6am, and the highest one during daytime, between 8am and 8pm. On the other hand, the relative humidity varies between 51% and 96% during the considered month. The highest values are observed in contrast to the temperature in the day and the lowest values at night. It can be taken as a whole that the increase in humidity causes the decrease in temperature.

4.2 Evolution of Indoor Hygrometry and Temperature (Reference Building)

Fig. 7 shows the hourly variation in indoor temperature and humidity in the main rooms of the house, for the standard basic case without insulation. The internal temperature of the main parts varies globally between 24°C and 35°C. The living room, due to its south-facing position and with large windows facing south, is characterized by a temperature slightly higher

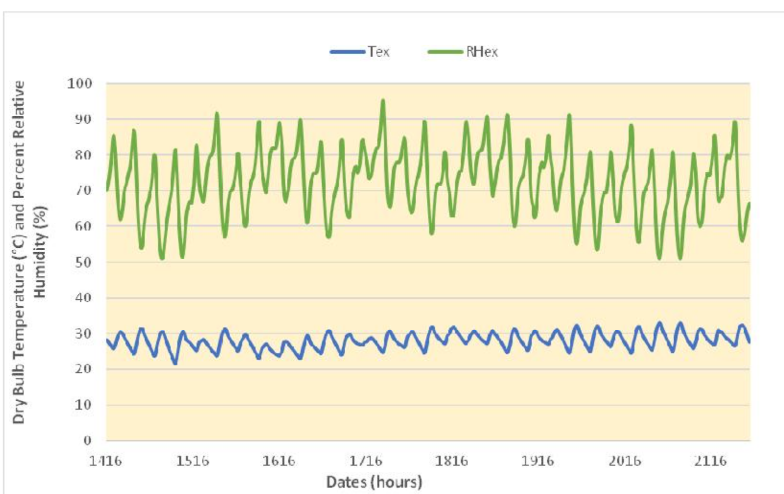

Fig. 6. Variation of outdoor temperature and humidity as a function of time over the month of March (Projet Impétus Bénin, 2007)

than those of the bedroom 1 and bedroom 2 which remain equal (24°C to 32°C). The temperature difference is of the order of 3°C. As a result, the indoor air temperature in the living room reaches 35°C during the day and stays above 27°C during the night. Thus, for the basic reference building, the thermal comfort is mostly not attained. The difference in temperature is also justified by the more regular presence of the family in the living room. Therefore, this relatively high temperature in the living room induces a mean humidity value (50%) lower than that of the rooms (70%).

Fig. 8 shows the hourly variation in indoor temperature and humidity in the service rooms.

The variations in the hygrometry of the service rooms have the same trends as before, but are much higher. The average humidity in the kitchen is 73%, the highest values are observed during the cooking phase of meals, because of the more significant releases of water vapour. In the bathroom (WC, shower), the humidity is higher than that of the kitchen with an average value of 77%. The peaks are obviously observed during shower takes. The average temperature is then 29°C. The temperature is out the comfort zone.

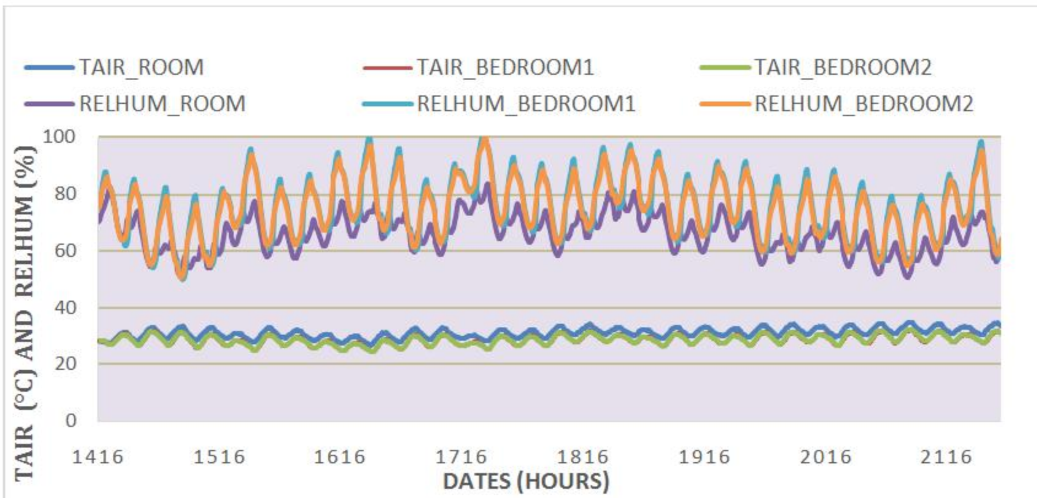

Fig. 7. Variation of relative humidity and temperature versus time in the living room, bedroom 1 and bedroom 2 over a month

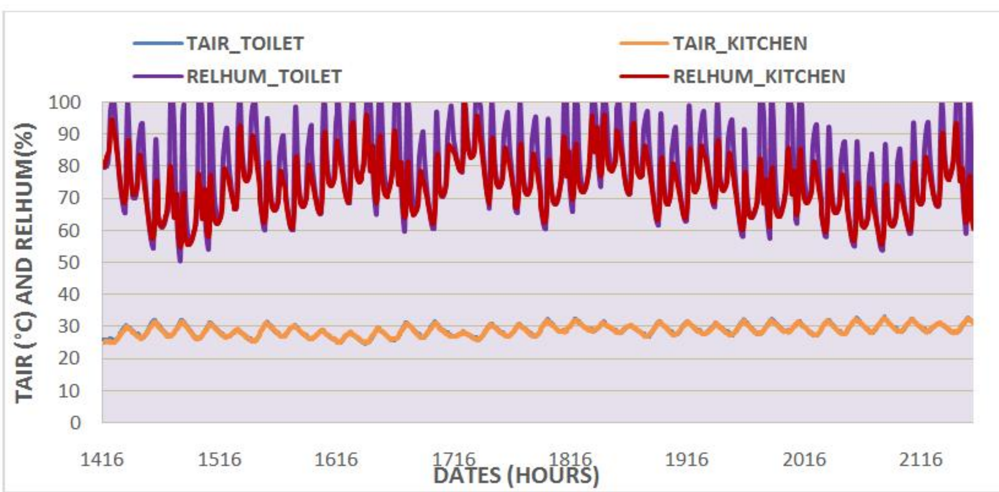

Fig. 8. Variation of relative humidity and temperature as a function of time in the kitchen, and the bathroom for the month of March

4.3 Evolution of the Cooling Requirements

The thermal load of the living room is higher compared to those of the 2 bedrooms whose cooling requirements are identical. The heat load of the living room reaches a maximum of 6990 kJ/h. On the other hand, the demands for refreshing of the toilet and kitchen are almost half that of the living room due to their more favourable exposure (Fig. 9).

4.4 Simulation of the Effect of Insulation on Thermal Comfort

Figs. 10 and 11 illustrate the impact of insulation on the thermal comfort in the living room, in terms of temperature and hygrometry time variations.

The results of Fig. 10a show that the insulation of the envelope and the roof, with 3 cm of polystyrene reduces the interior temperature of the living room of 3°C. For 5 cm and 10 cm, the reduction is 4°C, and 5°C for 15 cm thick. It is found that increasing the thickness of the insulation up to 15 cm significantly reduces the internal temperature. The same trend was observed by Fezzioui et al. [8] who found that increasing the envelope inertia decreases the heat load. The relative humidity reaches an average value of 71% for a thickness of 3 cm (Fig. 10b), meaning an increase of 6%, considering the humidity of the living room

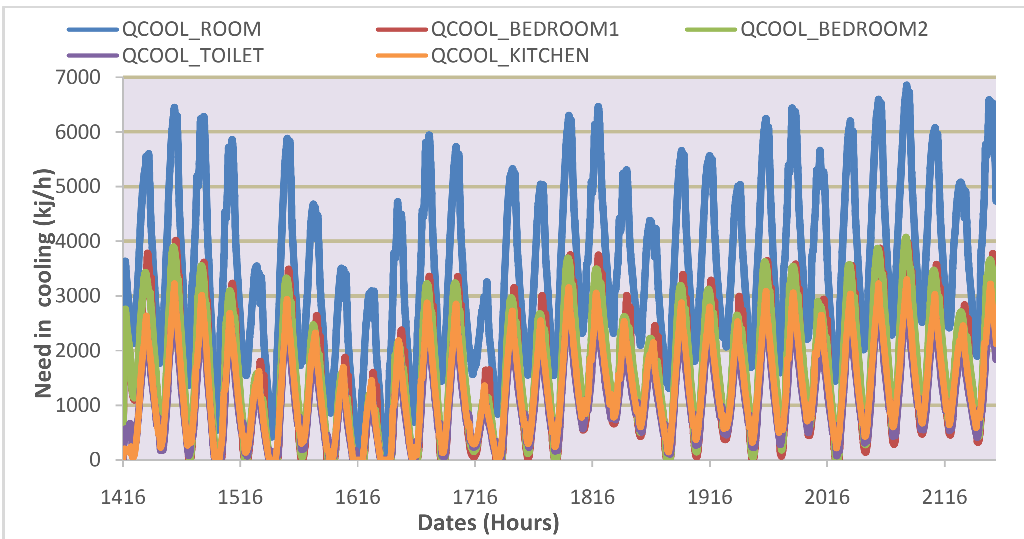

Fig. 9. Variation of the need for cooling in the standard house without insulation (in March)

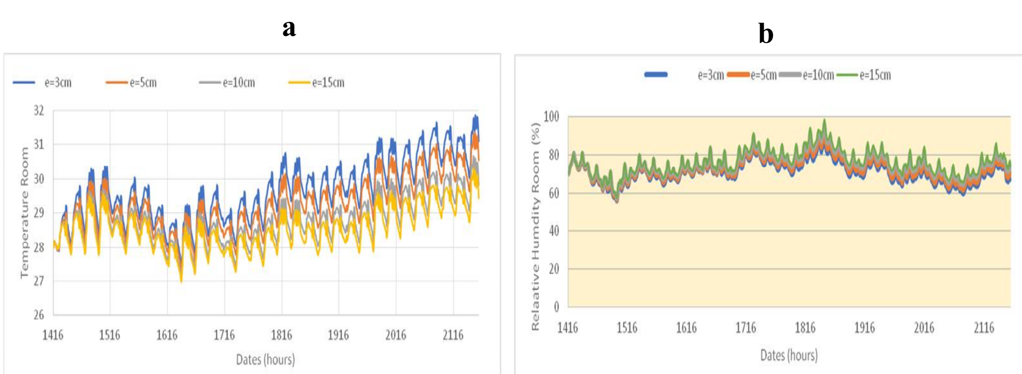

Fig. 10. Impact of various thicknesses of polystyrene on the thermal environment in the living room: (a) variation of temperature, (b) evolution of humidity as a function of time

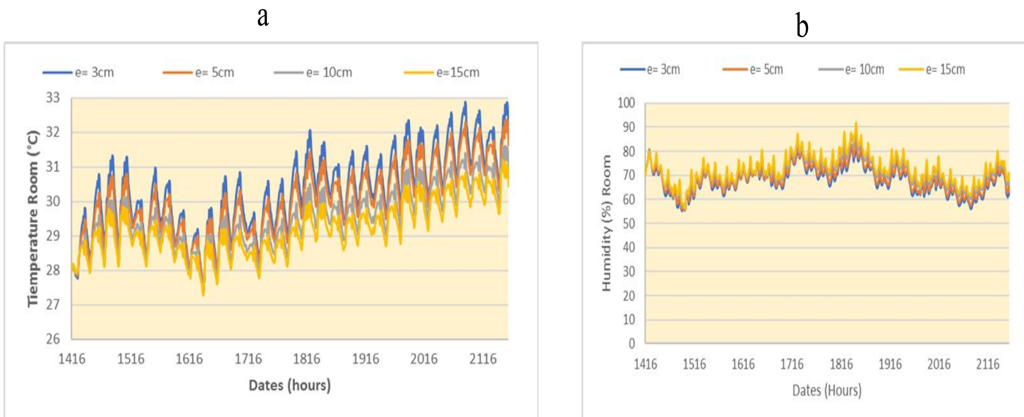

Fig. 11. Variation of the impact of different thicknesses of the straw insulator on the thermal environment in the living room: (a) variation of the temperature, (b) variation of the humidity in March

without insulation. In addition, the humidity increases up to 11% with the increase in thicknesses, as the insulation reduces the permeability of the walls. In the case of straw used as insulator (Fig. 11a), a thickness of 3cm of integral interior insulation reduces the internal temperature of the building of 2°C. The reduction is of 3°C for thicknesses of 5 cm and 10 cm, and is up to 4°C for 15 cm. A difference of 1°C is observed with respect to polystyrene, due to the slight difference in the thermal conductivities. But advantageously, the insulation with straw gives a relative humidity lower than that of polystyrene with a value of 68%, meaning 3% deviation (Figure 11b). This is a main reason for developing and promoting the use of this bio based insulation. Moreover the cost of straw is very cheap in the study area (Table 4).

Figs. 12, 13, 14 and 15 describe the impact of insulation on the thermal comfort in the bedrooms.

In the main rooms (Fig. 12a and Fig. 14a) the temperature difference is of 5°C with the thicknesses of 3 cm and 5 cm, compared to the basic configuration without insulation. The temperature oscillates globally between 22°C and 27°C. The thermal comfort is almost reached, considering only the temperature variation. For the thicknesses of 3 cm and 5 cm, the internal temperatures have respectively a reduction of 4°C, and of 2°C only for the thicknesses of 10 and 15 cm compared to the uninsulated reference case. The average humidity in rooms with 3 cm thick is 93%. It varies between 96% and 99%

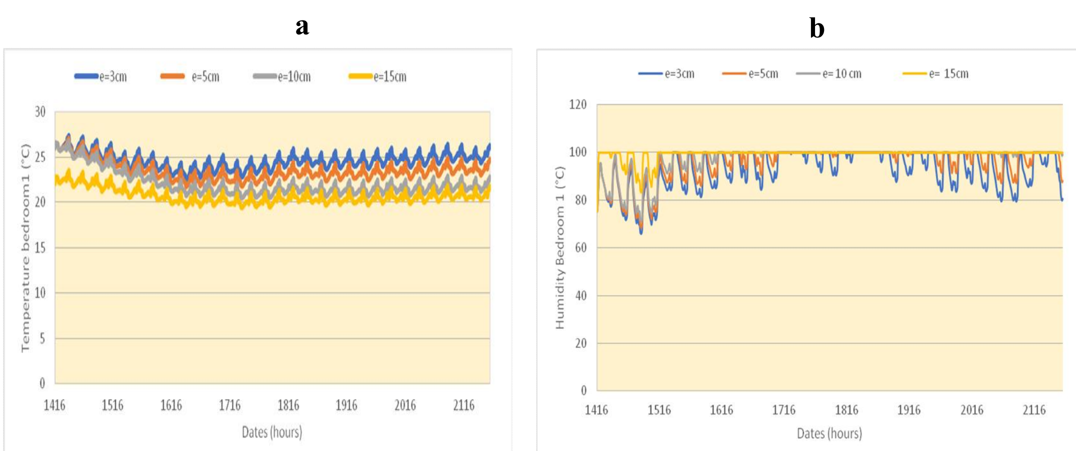

Fig. 12. Variation of temperature (a) and relative humidity (b) as a function of time over several thicknesses of polystyrene in the bedroom 1

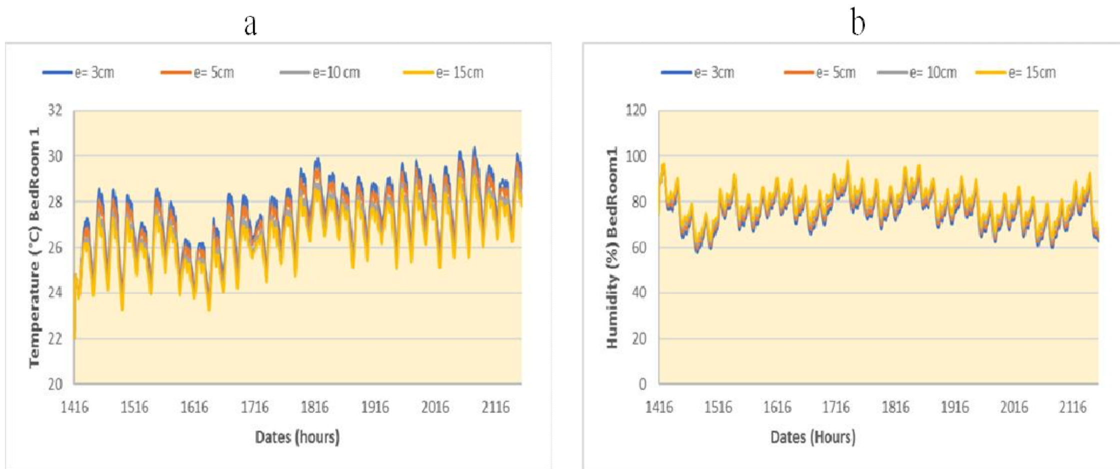

Fig. 13. Variation of temperature (a) and relative humidity (b) as a function of time over several thicknesses of straw in bedroom 1

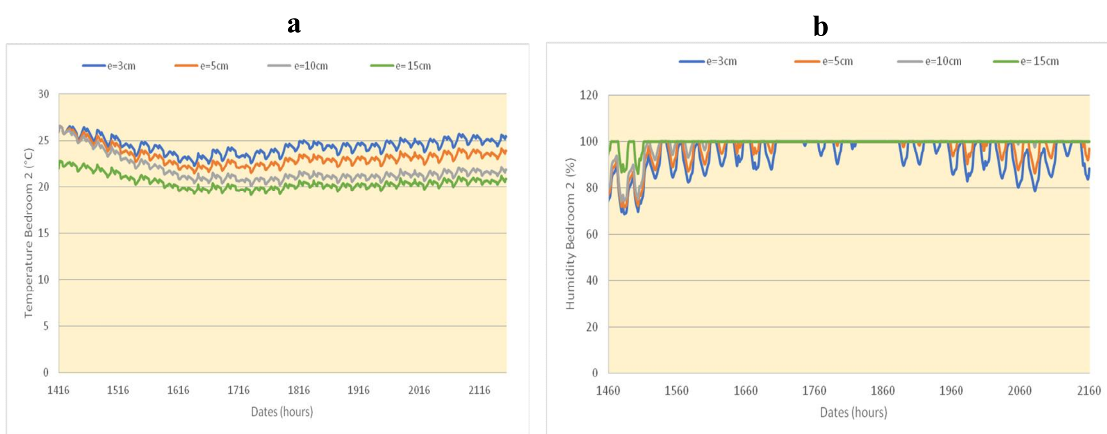

Fig. 14. Variation of temperature (a) and relative humidity (b) as a function of time over several thicknesses of polystyrene in the bedroom 2

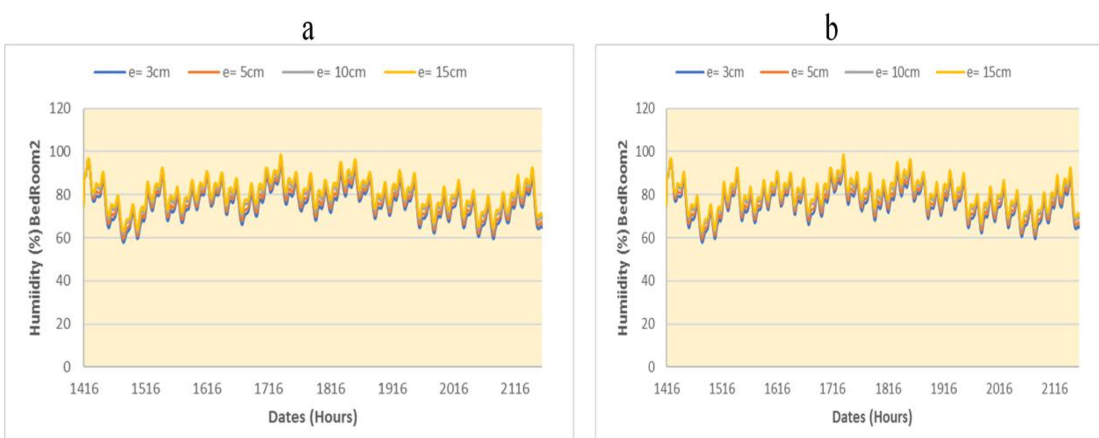

Fig. 15. Variation of temperature (a) and relative humidity (b) as a function of time over several thicknesses of straw in bedroom 2

(Fig. 12b, Fig. 14b) for other thicknesses. The high increase in humidity is due to the growth in tightness of the envelope resulting from the good insulation. Humidity comfort is not ensured with a high risk of moisture condensation on the walls and ceiling. The temperature difference is of 3°C, for both thicknesses of 3 and 5 cm in the rooms isolated with straw, meaning a variation between 22°C and 30°C. For the thicknesses of 10 cm and 15 cm, the internal temperatures are respectively of 2°C and 6°C higher than the polystyrene case (Fig. 13a, Fig. 15a). On the other hand, the insulation with the straw leads to slightly lower average humidity of 76% with thicknesses of 3cm and 5cm, and 80% for thicknesses of 10cm and 15cm (Fig. 15a, Fig. 15b). Noteworthy that the thicker the insulation is, the higher becomes the resulting indoor hygrometry.

Figs. 16, 17, 18 and 19 show the influence of insulation on thermal comfort in service rooms (kitchen and bathroom).

4.5 Determination of Optimal Polystyrene Thickness According to Costs

To find the optimum insulation thickness, a comparison was made between the insulation cost and the one related to the artificial cooling in Benin contexts. Insulation costs increase with the insulation thickness, while the energy consumption related to artificial cooling decreases to some extent with thickness.

It can be seen in Fig. 20, that the increase in the cost of insulation follows the increase in the insulation thickness, whereas the need for cooling decreases. The cross point at 3 cm of

a b

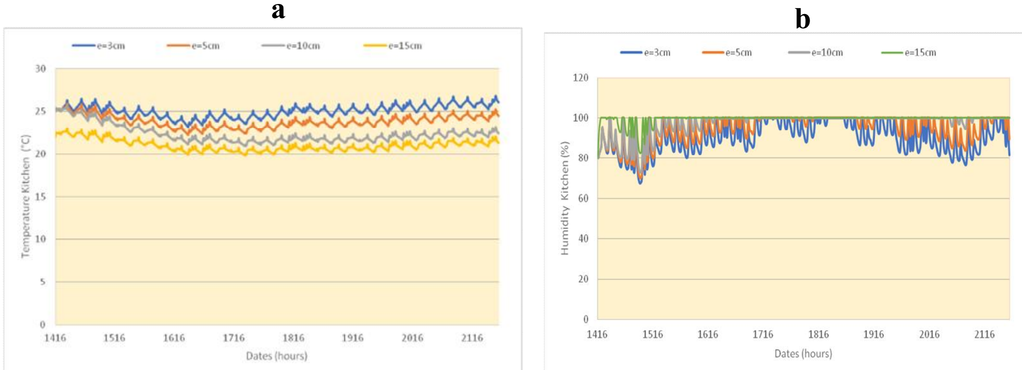

Fig. 16. Variation of temperature (a) and relative humidity (b) with several layers of polystyrene in the kitchen

a b

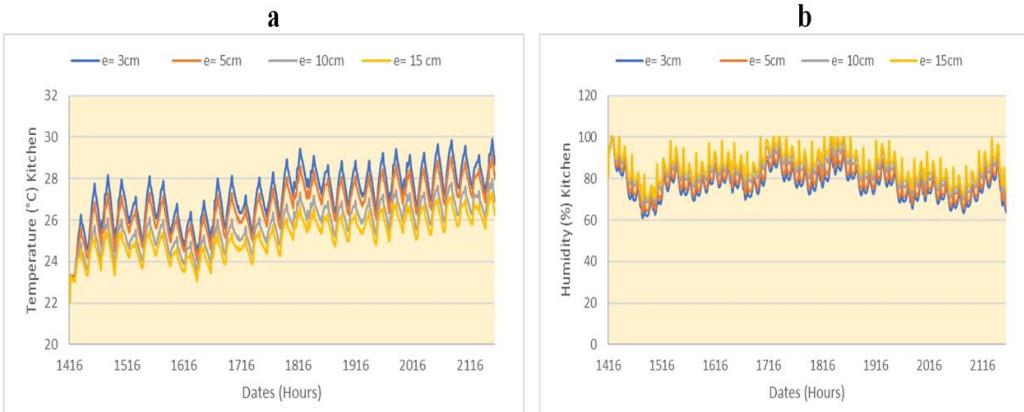

Fig. 17. Variation of temperature (a) and relative humidity (b) with several layers of straw in the kitchen

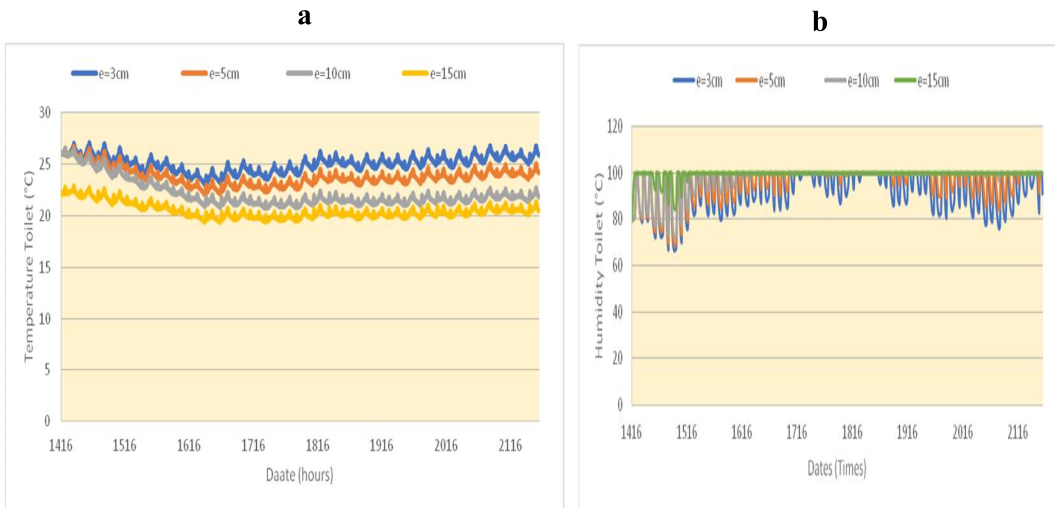

Fig. 18. Variation of temperature (a) and relative humidity (b) as a function of time with several layers of polystyrene in the bathroom

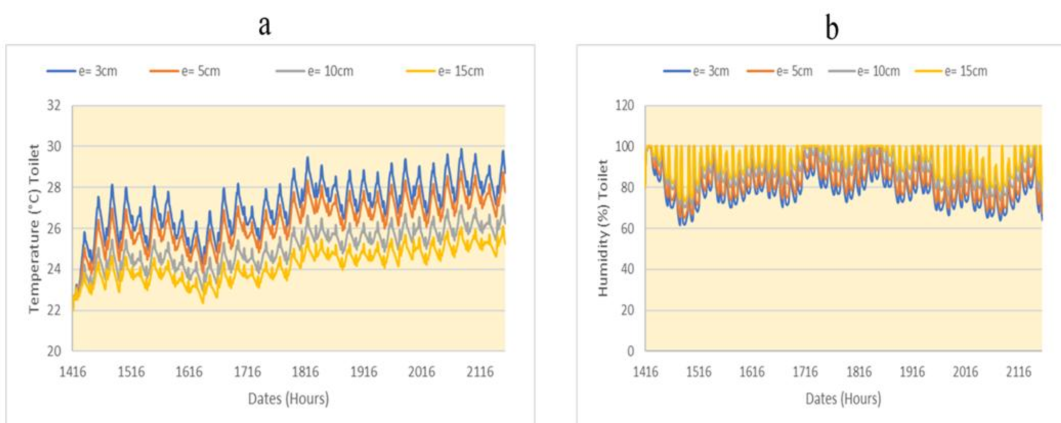

Fig. 19. Variation of temperature (a) and relative humidity (b) as a function of time with on several layers of straw in the bathroom

thickness is the optimized value. The optimal thickness of insulation is the thickness which gives better energy saving for a lower cost of insulation. For similar investigation, an optimum of 6cm was proposed by Guechchati et al. [11]. But optimal thicknesses are correct only within local contexts as they depend on energy and material costs, outside air conditions, type of insulation (external or internal), envelope materials, etc.

But polystyrene being an imported product is expensive, with a less favourable environmental impact than straw. The latter is abundantly available locally and has indisputable ecological advantage. In addition, its implementation would be cheaper compared to manufactured and imported insulations. Its sector (production, transformation into ready-to-use and sustainable construction material) would help improve the carbon footprint of buildings in Benin. On the other hand, the problem of optimization by the cost of insulation would not arise so much, and thicknesses greater than 3 cm can be calmly considered for this ecological insulation.

Overall, the interior insulation of buildings reduces temperatures and decreases the need for artificial cooling. But, it increases the humidity in all rooms. One solution is to provide mechanical ventilation to maintain proper moisture levels for human hygiene and sustainable aging of building materials.

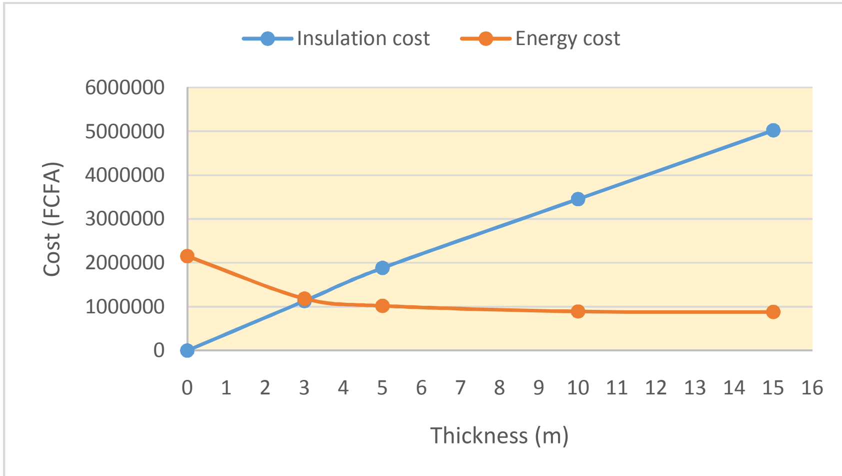

Fig. 20. Variation of insulation and cooling energy costs in function of the insulation thickness

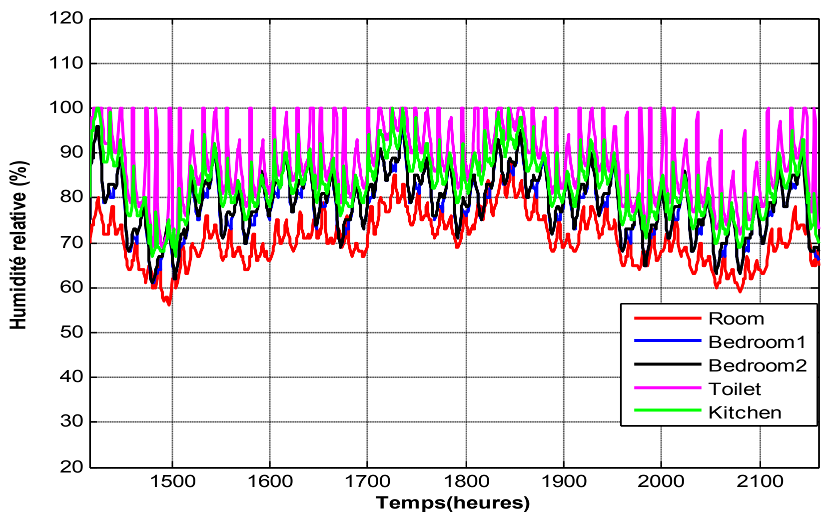

Fig. 21. The effect of controlled mechanical ventilation on hygrometric comfort

4.6 The Effect of Controlled Mechanical Ventilation on the Humidity

This study is conducted only for polystyrene. For the simulation, the thickness of 3 cm of extruded polystyrene was considered for an integral insulation of the housing. The controlled mechanical ventilation is installed to reduce humidity through the provision of dry outdoor air and the extraction of stale humid air. The amount of hygienic air flow introduced at outdoor air conditions is 150 m^3/h. The extracted exhaust air flow is of the same value.

The integration of mechanically controlled ventilation reduces humidity of 2.5% in the living room, of 24% in bedrooms 1 and 2, and 25.5% in the service rooms. Therefore, it can be deduced that the blowing of hygienic air and the extraction of polluted humid air improves the hygrometric comfort and makes it possible to obtain a range from 67% to 76% in humidity, which corresponds to the standard of the comfort zone. Thus, coupling insulation and ventilation leads to thermal and hygrometric comfort.

5. CONCLUSION

The effects of the insulation of the building with polystyrene and straw have been studied for several thicknesses in tropical environment to ensure a better atmosphere and reduce energy consumption related to artificial air conditioning.

Two occupancy scenarios were defined corresponding to working days and weekends. The modelling of the house with the integration of polystyrene insulation under the software TRNSYS has reduced the temperatures in the room of 3°C to 5°C, and of 2°C to 5°C in rooms 1 and 2, and finally by 5°C to 9°C in the service rooms. On the other hand, relative humidity increased from 6% to 11% in the living room, by 25% in the bedrooms and 24% or even 30% in the toilets. Insulation with straw, reduces the indoor temperature of 2°C up to 4°C in the living room, and by 2°C to 6°C in rooms 1 and 2, then of 5°C to 9°C in the service parts. The straw insulation reduces humidity by 3% in the living room, but increases it from 4% to 8% in rooms 1 and 2, and finally by 12% in service rooms. In terms of optimizing the thickness of polystyrene, the results make it possible to target a thickness of 3 cm as a good compromise in the reduction of energy cost. Larger thicknesses would encroach on the interior living space and the cost of implementation, without a guarantee of a convincing thermal improvement. This thickness of 3 cm directly reduces the consumption of electrical energy of a hypothetical air conditioning system. But the integration of the mechanically controlled ventilation made it possible to purify the air and to evacuate humidity. Moreover, it reduces the relative humidity at the respective rates of 2.5%, 24% and then 25.5% in the living room, bedroom 1 and 2, and finally in the kitchen and the bathroom to comply with the standards of comfort.

It can also be noted that the simultaneous integration of insulation and controlled mechanical ventilation makes it possible to be free from the air conditioning while ensuring an irreproachable and better quality of air unlike the majority of the air-conditioning premises in western Africa without contribution of hygienic air. Finally, the reuse and the promotion of straw as a sustainable building material should be considered for its good insulation performance and low environmental impact, along with a relatively cheap global cost.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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ANNEX

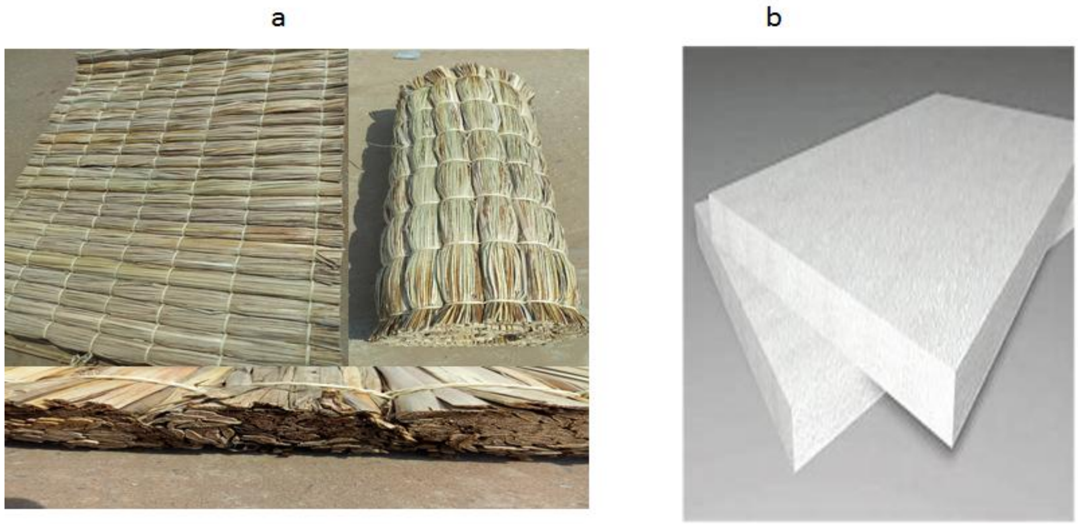

Fig. 22. Insulators (a) Local straw; (b) Acermi certificated extruded Polystyrene

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