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RESEARCH ARTICLE

STUDY OF THE IMPACT OF THERMAL INPUTS BY ROOFS ON THE HYGROTHERMAL COMFORT OF HABITATS IN TROPICAL ENVIRONMENT

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ABSTRACT

Most of the houses in Benin are built randomly, with arbitrary orientations and unsuitable materials. This lack of rigor in the design of edifices and the inappropriate choice of materials lead to the construction of premises that do not meet the climatic requirements and lead to excessive energy consumption in case of air conditioning. Thus, the purpose of this work is to explore the suitability of various local roofing materials eligible for the construction of residential premises and to analyze their impact on the overall thermal and environmental performance of houses. To achieve this, four different roofs were tested on a building chosen as a model. The thermal contributions of these different roofs, as well as the energy consumption, were determined by dynamic thermal simulations in order to apprehend the thermal behavior of the chosen building. The TRNSYS software was used to model the building and perform the various simulations. The study showed that the straw roof reduces the need for cooling by 37% compared to the reference building whose roof is made of concrete slab. With the terracotta tile roof, the heat load is reduced by 15%. On the other hand, the zinc sheet roof increases the cooling requirement by 40% compared to the concrete slab benchmark. The study revealed that there exists an economic and environmental interest to develop roofing made from local materials such as straw and terracotta.

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INTRODUCTION

Energy consumption in the building sector accounts for about 30% of the energy used in the world (Document, 2006). In Europe, buildings account for almost 40% of the primary energy consumption (Roberto, 2017). This is a prime target for improving energy efficiency (Antoniadou P. *et al.*, 2017). The energy consumption of public and private tertiary sector buildings in sub-Saharan Africa is between 250 and 450 kWh/year and per m² of the air-conditioned area (Document, 2001). Depending on the quality of buildings, Heating Ventilation and Air Conditioning (HVAC) systems account for 50 to 70% of buildings' electricity consumption. Benin is no exception. Over the last 13 years, its energy consumption has been steadily increasing in the residential sector, still leading other sectors, with an average growth rate of 5.3%. In the same sector, electricity consumption in households is growing at 11% over the same period (Rapport, 2010). As a result, the minimization of the energy bill is a priority intervention for the Beninese State through the introduction of a policy to improve energy efficiency in the building sector. In Cotonou, for roofing, most of the population adopts sheet metal as roofs, a financially accessible and imported manufactured material. Other covers such as tiles or concrete slabs (see ANNEX) are adopted rather by the so-called middle and upper social classes who opt for the construction of massive habitats without regard to climate or worrying about the energy performance of the building. The thermal loads of a building can be reduced considerably in tropical regions by the combination of an effective solar protection of the envelope (roof, walls, bay windows) and the providing of an adequate air flow to evacuate heat and to create on the occupant's significant airspeed (which contributes to a better comfort). Some studies have focused on the influence of the envelope on the energy performance of buildings in Africa. However, Sub-Saharan Africa remains the part of the terrestrial globe where very few investigations have been made on the thermal

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behavior of buildings (Aurélien *et al*., 2016). Few studies have been carried out on the use of local materials such as straw or mud, although (Dreyfus J., 1960) has shown that the traditional architecture of West Africa offers greater comfort to the occupants. Especially in Benin, the dynamic thermal simulation of buildings is still embryonic. Olissan used the TRNSYS software to evaluate the impact of window glass on thermal comfort (OLISSAN Olagoké Aurélien, 2017). (Comlan Aistide HUANGAN, 2008) carried out investigations on the hydrometric characterization of local materials used in habitats in Benin. (Sibiath Omolola G. OSSENI, 2017) conducted studies on the thermo-mechanical characterization of mortars reinforced by fibers of the banana trunk [8]. These mortars have better thermal properties and high flexural strength for composites containing 3-4% fiber (such materials are named Class B samples). (Necib *et al*., 2016) showed that the roof is responsible for 70.62% of overall thermal gains. The roof then constitutes an effective solar protection if the materials of its design are insulators. The general observation concerning Benin is that no study made a focus on the influence of the local materials used in a building envelope on the thermal comfort. Accordingly, the objective of this study is to investigate through simulations, the best roofing material that reduces thermal gains in building construction and provides good environmental performances (Roberto Garay Martinez, 2017).

MATERIALS AND METHODS

To start, a study has been achieved on the thermal performances of the “reference” house built with hollow blocks and the paved roof. Then in a second step, the thermal behavior of three roofing variants (straw, zinc sheet and terracotta tile) was studied in details on the same building to identify the one that allows the greatest economy of energy in the case of air conditioning. This quantitative study is based on the dynamic thermal simulation of the building using the software TRNSYS 17 (TRNSYS Version 17, User Manual’) for the hottest month of the year (March). For each case, the thermal behavior of the building is evaluated through the convective heat flux in the building which represents the demand for cooling.

Materials

Description of the reference building: The studies are carried out on a typical residential building in Benin located in Cotonou with the following geographical coordinates: Latitude 6°38'N, Longitude 2°34 'E. This is an F4 housing of the middle class in Benin with a living room, three bedrooms, a bathroom and a kitchen (Fig.1). The edifice is built on a floor area of 98 m² and the roof is concrete. The main entrance to the building is located on the south facade (Fig.2). The openings of the building face the four cardinal points and ensure this way the natural ventilation of the spaces. Fig. 3 shows the composition of the wall, floor and roof. The wall is built with hollow bricks 15 cm thick and is plastered on the outside with a cement coating (2 cm thick). The inner side of the walls is covered with a coating of cement plaster of 2 cm. The walls of the partitions have the same composition as the outside ones.

Input data

The software required the local meteorological data (temperature, relative humidity, radiations …) to operate. But as such data were not available for the investigated area; the meteorological file of Lagos, the neighbor Nigerian town was taken into account. This town is less than 100 km from Cotonou and has almost the same climate as the coastal strip of Benin. Fig. 4 (a) shows the annual change in air temperature. It is observed that temperatures between 24 and 34˚C are the most frequent in this region. Temperature is above 30˚C in the hottest months. It reaches its highest value in January, March and October, and the lowest one in December, July or August. Fig. 4 (b). displays the monthly change in March outdoor air temperature. Fig. 5 (a) shows the change in relative humidity throughout the year. The lowest values for relative humidity are between November and March, mid-July and mid-September. This happens in the dry season. But the highest values appear between April and July, mid-September to October with a peak in August during rainy seasons when they exceed 90%. But overall, the humidity of the air remains higher than 50% throughout the year. Fig. 5(b) presents the monthly change in the relative humidity of outside air in March. Fig. 6 (a) displays the change in global radiation, normal direct, diffuse radiation over the year, and Fig. 6 (b) zooms in during the first week of January.

Global horizontal irradiance varies between 0 and 3053 kJ/ (h.m^2), equivalent to 848W/m^2, which is higher than direct and diffuse insolation. This difference is explained by the fact that global irradiation is the sum of diffuse and direct irradiations. The simultaneous null value of the three irradiations is observed at night because of the absence of the sun. The various irradiations take sometimes small values due to the reduction of the intensity of solar radiation with the presence of clouds. Globally, peak values of different irradiations are high given the tropical climate.

Methods

Mathematical model to determine the demand for cooling: The convective heat flux in the building is governed by the following equations (Document, 2014):

The meanings of the various expressions of the heat balance (1) are presented in the Nomenclature:

$$Q_T = Q_{surf} + Q_{\inf} + Q_{vent} + Q_{gain} + Q_{cp\lg} \tag{1}$$

With;

$$Q_{\inf} = \rho_a \; V \; C_a (T_{ext} - T_i) \tag{2}$$

$$Q_{vent} = \rho_a \; V \; C_a (T_{ventilation,i} - T_i) \tag{3}$$

$$Q_{surf} = h_c \; \rho_a \; C_a (T_{s,i} - T_i) \tag{4}$$

$$Q_{gain} = h_c \; \rho_a \; C_a (T_{s,i} - T_i) \tag{5}$$

$$Q_{cp\lg} = \rho_a \; V \; C_a (T_{zone,i} - T_i) \tag{6}$$

In this case study, as the building is naturally ventilated, the heat load linked with running of fans is zero. The model used in TRNSYS for the heat transfer on the surfaces of the walls is as follows (Stephenson, D.G. and Mitalas, 1971; Mitalas, G.P. and Arseneault, 1972; Lechner, T, 1992):

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \tag{7}$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,o}^k \tag{8}$$

These time series equations in terms of surface temperatures and heat flux are evaluated at equal time intervals. The exponent k refers to the term in the time series. If the current time is at k = 0, the next time is k = 1, and so on. The time base on which these calculations are performed is specified by the user in the TRNBuild description. The coefficients of the time series (a, b, c and d) are determined in the program TRNBuild using the reference transfer function z (C.K. Cheung *et al.*, 2005). At the beginning of the modelling, the geometric and thermo-physical description of the building has to be completed.

Modeling hypotheses

The building is in free evolution, meaning that it's not equipped with any energy system to condition it. The hypotheses adopted for the simulation are the following:

- internal contributions to have results close to local reality, namely:
    - the house sheltering four people;
    - a set of 230W electronic equipment;
    - a lighting package of $5 W/m^2$
- the initial temperature and humidity are taken equal to 26°C and 60% respectively;
- the air infiltration coefficient is 0.6 volume/hour.

Composition of the envelope: The dimensions of the building of reference, as well as its geometric form, are modelled with the aid of the software Google SketchUp to build the 3D graphic of the house. It is to create each part of it (the walls, the doors and windows…), then to bind the surfaces to establish a thermal connection between adjacent rooms. The building is considered as one single zone since the different rooms share the same air. According to (Madi Kaboré, 2015), this one-zone nodal model takes into account partitions within the zone that are modelled as internal masses. The thermophysical properties are reported in Table 1. The windows of the house are single glazed. They have an overall heat exchange coefficient of 5.74 $W/(m^2.K)$, and a solar factor of 0.87.

Once the structure of the building was conceived, the insertion of the thermophysical data of the walls, floor and ceiling was implemented within TRNBuild functionality of TRNSYS. In fact, we specify the composition of the walls, their respective orientations, the glazed surfaces and the types of glazing used. It is also necessary to define the initial conditions of the considered zone (the indoor temperature and the relative humidity), the control parameters of the cooling as well as the internal heat contributions. The software includes many building materials, but it is still possible to define its own materials. Indeed the library of TRNSYS does not have some of the materials needed for the current simulation. So these materials have been created. Each of the materials is accompanied by additional information such as the type of layer (massive, without mass, active). In the present case, it is a massive layer to which the thermal conductivity, the specific heat and the density are added.

Properties of the proposed variants: The building envelope plays a role of thermal separation between the indoor and outdoor environment. It acts as a receptacle (or storage) of heat in the building and as a propagator of it in indoor and outdoor air (C.K. Cheung *et al.*, 2005; N. Safer, 2006) . In a first approach, the thermal performances of three types of materials were tested in addition to the reference building: straw, zinc sheet, terracotta tile and concrete (Table 2). The thermo physical characteristics of the variants are described in Table 3 (Madi Kaboré, 2015; Document, 2014).

Environmental impact: The environmental impact is quantified with the TEWI, in order to evaluate the CO_2 emissions linked to a hypothetical artificial cooling required to remove away the heat influxes by the roofs. The TEWI (Total Equivalent Warming Impact) is the sum of the direct and indirect greenhouse effect of the cooling load. It represents the equivalent mass of CO_2 released during the life cycle of the refrigeration plant. The TEWI is expressed by the following relation:

$$TEWI = GWP \times M[(1-X) + (f \times N)] + (E \times A \times N) \quad [kg\ eq\ CO_2], \tag{9}$$

Where

- GWP means the Global Warming Potential, GWP_{R410A}= 2088 [kg eq. CO_2],
- M is the mass of Refrigerant within the equipment (estimated as 5kg per kW cooling capacity); $M = 0.5 \times P_{cooling\ capacity}$
- x=80%, fraction of fluid recovered at the end of the plant's life.
- f=15%, annual leakage rate (f % of M).
- N lifetime of facilities = 15 years (on average).
- E annual energy consumption of equipment. The average Coefficient of Performance (COP) is estimated at 2.5.
- A is the rate of CO_2 released to produce 1 electric kWh. For an electricity production provided by a diesel engine, A = 0.3 [CO_2 kg eq. / kWh].

The annual consumption on an average operating basis of 22h / day and 365 days / year can be expressed as:

E = P_{elec} x 22 x 365 [kWh/an], with

$$P_{elec} = \frac{P_{cooling\ capacity}}{COP} \qquad [kW_{électrique}],$$

where P_{elec} is the electric power capacity of the equipment and $P_{cooling\ capacity}$ is linked to the heat load through the considered roofing.

NOMENCLATURES

Notation	Unity	Meaning
$\dot{Q}_{inf}$	*kJ/hr*	*Gain by infiltration with the outside air flow*
$\dot{Q}_{vent}$	*kJ/hr*	*Heat gains due to the running of fans*
$\dot{Q}_{surf}$	*kJ/hr*	*Convective heat flux of any interior surface*
$\dot{Q}_{gain}$	*kJ/hr*	*Inner convective inputs (lighting, occupants, household appliances)*
$\dot{Q}_{cplg}$	*kJ/hr*	*Heat load due to the convective air flow of an area*
Q_T	*kJ/hr*	*Global energy balance*
$s_{s,i}$	*kJ/hr*	*Radiation heat flux absorbed at the inner surface (solar and radiative gains)*
$S_{s,o}$	*kJ/hr*	*Radiation heat flux absorbed at the outer surface (solar gains)*
T_f	*K*	*Fluid temperature*
T_i	*°C*	*Indoor temperature*
T_P	*K*	*Wall temperature*
$T_{s,i}$	*°C*	*Temperature of the inner surface*
$T_{ventilation,i}$	*°C*	*Ventilation air temperature*
$T_{zone,i}$	*°C*	*Indoor air temperature of an area*
$\dot{T}_{s,o}$	*°C*	*Outside surface temperature*
$\dot{T}_{ext}$	*°C*	*Outside air temperature*
$\dot{V}$	*m^3/s*	*Air volume flow rate*
$\dot{q}_{s,i}$	*kJ/hr*	*Conduction heat flow from wall to interior surface*
$\dot{q}_{s,o}$	*kJ/hr*	*Conduction heat flow from the wall to the outer surface*
ρ_a	*kg/m^3*	*Density of air*
C_a	*kJ/kg.K*	*Specific heat of the air*
h_c	*KJ/kg.K*	*Coefficient of heat transfer by convection*

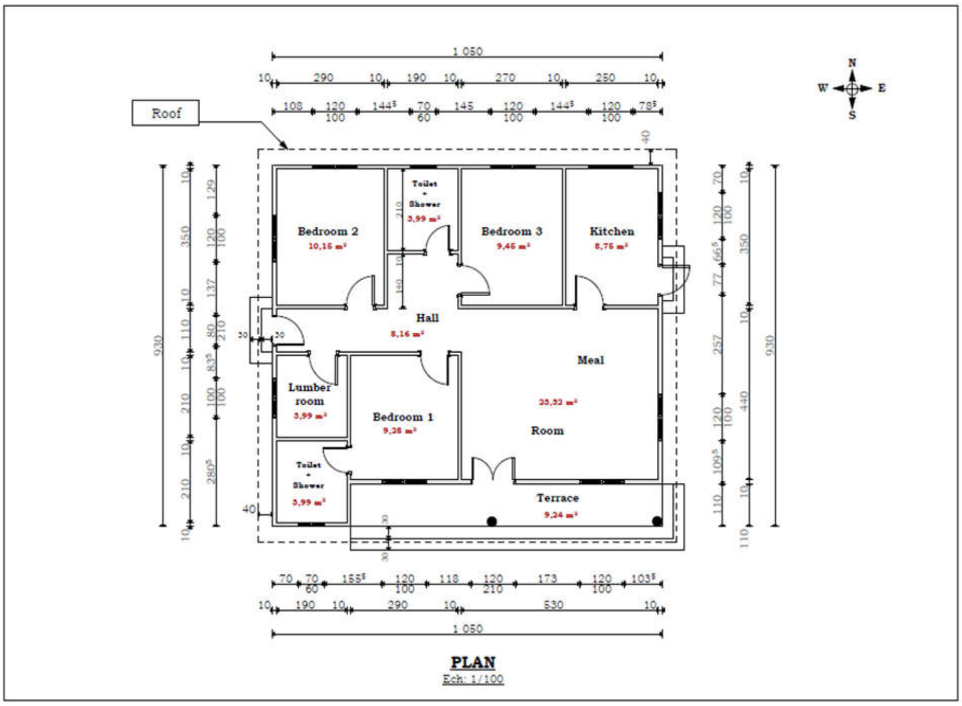


Fig. 1. Building plan view

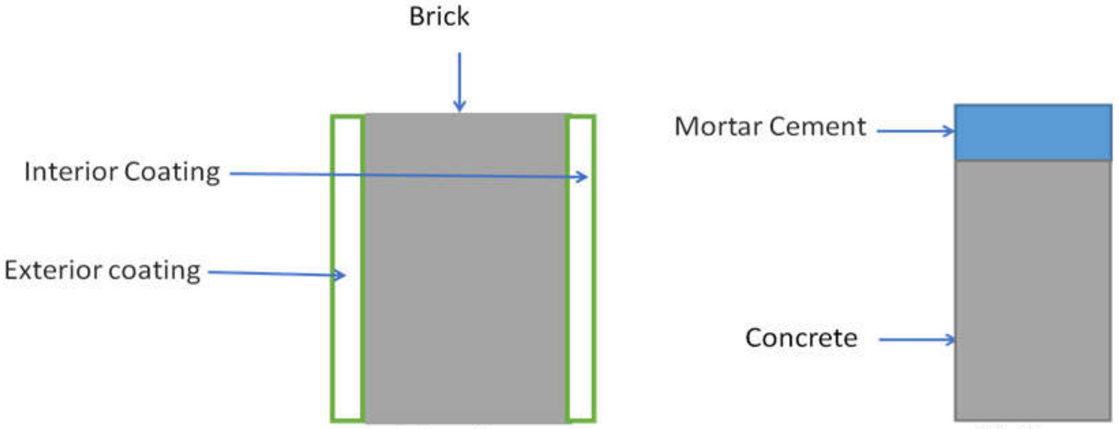
(a) South facade

(b) North facade

(c) East facade

(d) West facade

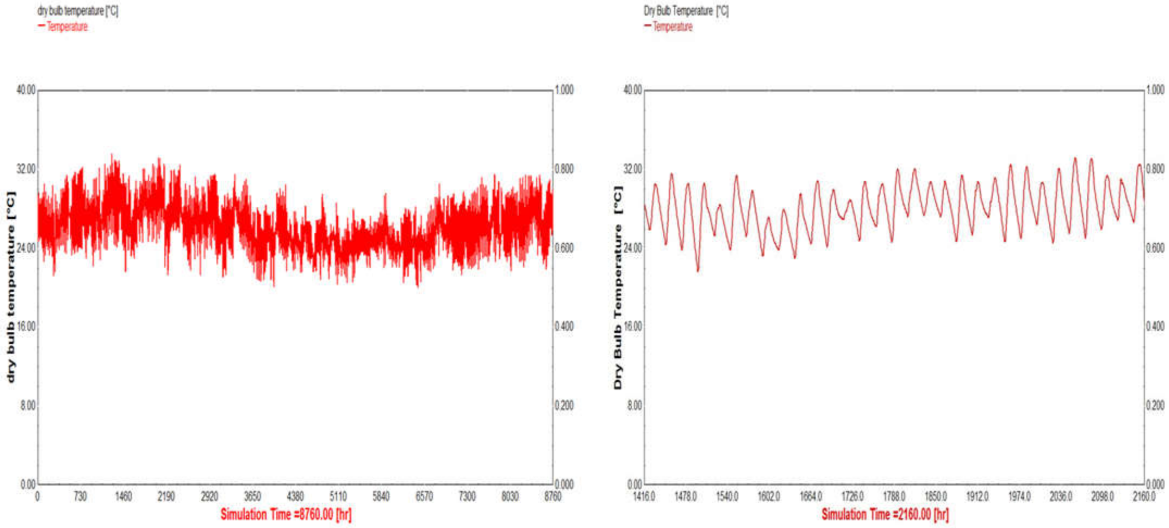
Fig. 2. Main facades of the building



(a) wall

(b) Floor

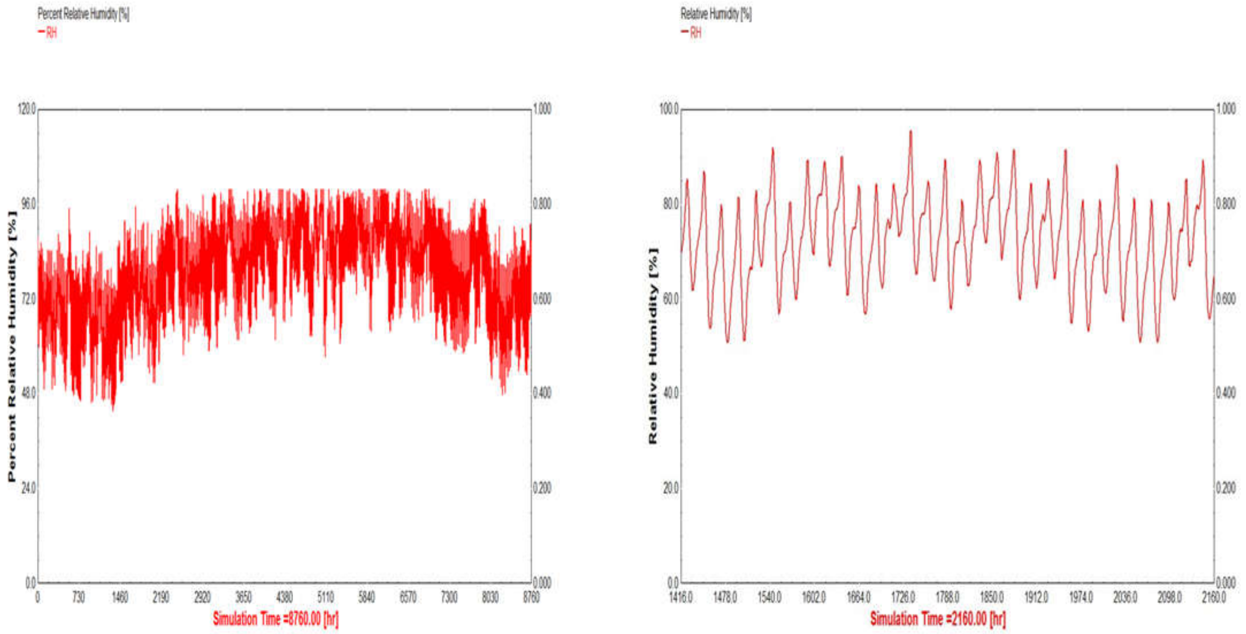
Fig. 3. Composition of wall and floor



(a) temperature in a year

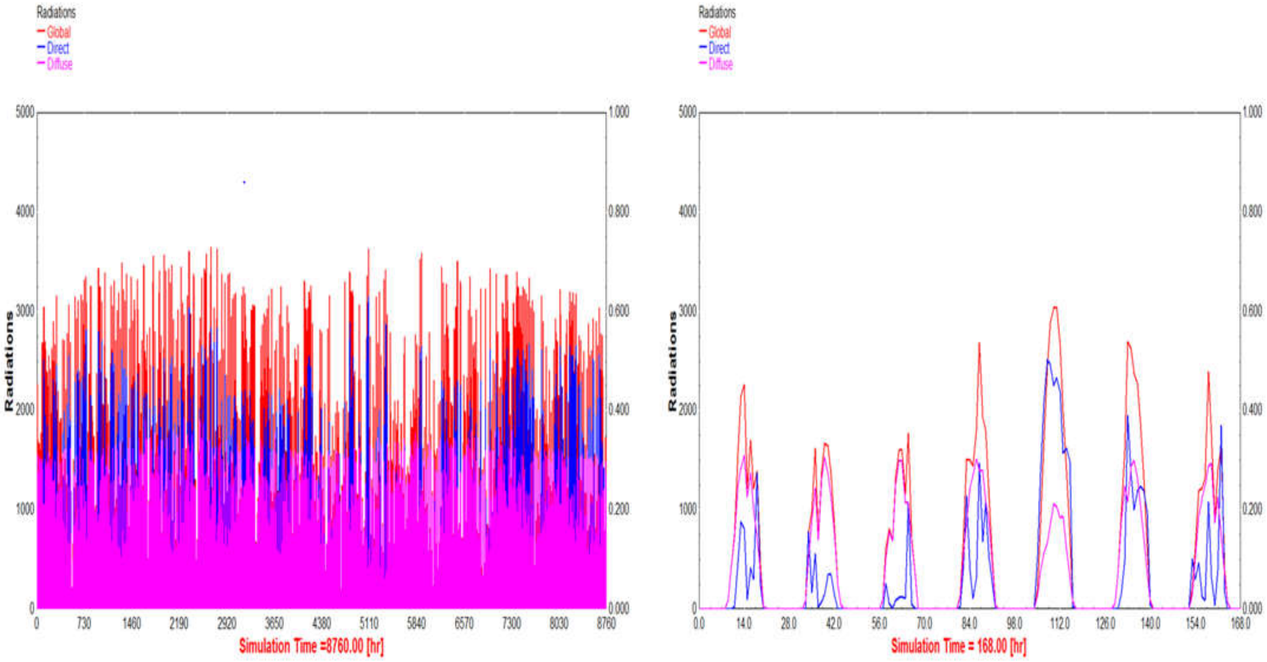
(b) temperature in a hot month

Fig. 4. Variation of ambient temperature



(a) humidity in a year (b) humidity in a month

Fig. 5. Variation of relative humidity



(a) radiations in a year (b) radiations during the first week of January

Fig. 6. Global horizontal, diffuse and direct radiation

Table 1. Thermophysical properties of materials

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
Roofing	Exterior cement plaster	0.02	1.15	1000	1700
	Concrete slabs	0.2	1.4	1001	2200
Floor	Smooth cement plaster	0.02	1.15	1000	1700
	Concrete	0.1	1.4	1001	2200

Table 2. Diverse variants proposed for the simulation

Type of wall	Variants	Description
Roof	0 (Current state)	Concrete roof
	1	Zinc sheet roof
	2	Straw roof
	3	Roof tile terracotta

Table 3. Thermo physical properties of the studied variants

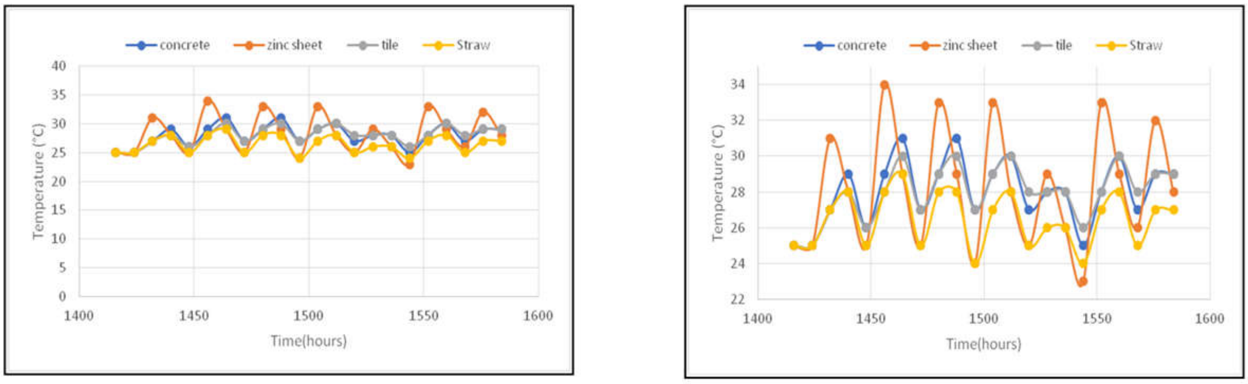
Type of roof	Width (m)	Thermal conductivity (W/mK)	Heat capacity (J/kg.K)	Density (Kg/m^3)
Zinc sheet	0.03	50	450	7800
Straw	0.45	0.07	1700	100
Terracotta tile	0.02	1	800	1700

Table 4. Variation of thermal gains through the investigated roofs

Roofing	Maximum cooling requirement (kJ / h)	Variation of thermal gains in%
Concrete	4448	0
Straw	2772	-37
Zinc sheet	6219	+40
Terracotta tile	3736	-16

Table 5. Annual Energy Requirement

	Reference construction (Concrete roofing)	Straw roof	Zinc sheet roof	Terracotta tile
Annual need for air conditioning (kWh)	44600,83	18415,53	48702,68	49134,52
Energetic performance (kWh / m^2 year)	637, 17	263,07	695,75	701,92



(a) variation for different cases

(b) zoom between 22 and 35°c

Fig. 7. Variation of internal temperatures

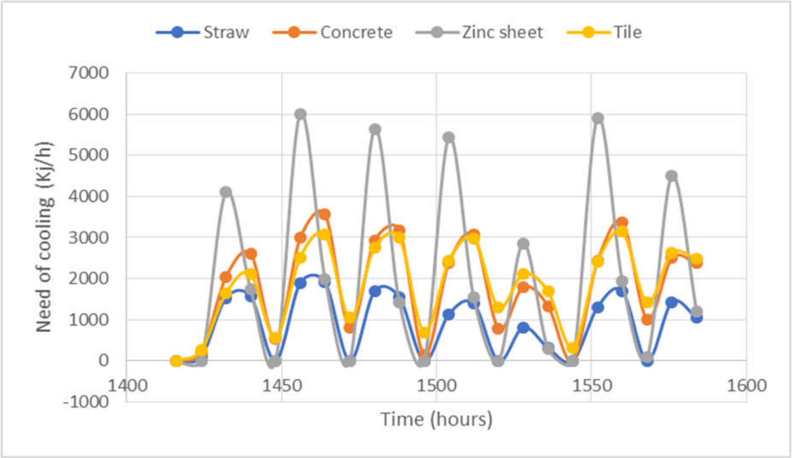


Fig. 8. Variation of the need in cooling for the different cases

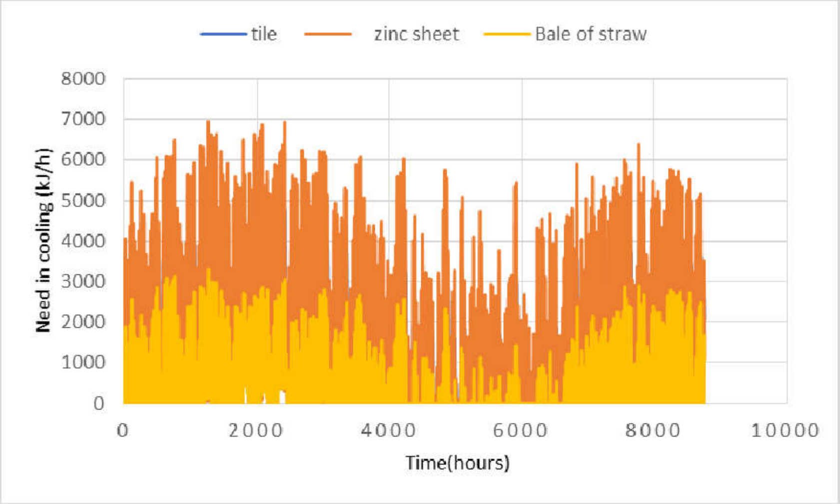


Fig. 9. Annual need for air conditioning (cooling)

Table 6. Evaluation of TEWI across different roofs

	Reference Building (Concrete Roofing)	Straw roof	Zinc sheet roof	Terracotta tile
Cooling capacity [kW]	16	10	22	13
E[kWh/an]	48180	32120	70664	41756
TEWI [kg eq CO2]	219944.3	144542.3	317990.3	187904.3
CO_2 eq gain (relative to concrete)	0	-33	+44	-15

Quantification of the TEWI is performed and discussed according to the different cooling capacities (need for cooling) corresponding to the reference roofing and the different variants (see next heading).

RESULTS AND DISCUSSION

Variation of the Indoor Temperature: Fig. 7(a) and its magnification Fig. 7(b) display the indoor ambient temperatures that would prevail in the reference house, if covered with a zinc roofing roof, a roof tile or straw instead of concrete. The results show that the building with the straw roof gives minimum interior temperatures (2°C - 27°C), with small fluctuations in temperature. On the other hand, the model with the roof in zinc sheet provides maximum internal temperatures (33°C, 34°C) with a strong fluctuation. The zinc roofing roof displays the greatest temperature variations (amplitude of 10°C). Terracotta and concrete tile roof have produced fairly large and almost similar temperature variations; they oscillate between 26°C and 30°C). For straw, the temperature range is much more moderate (2.5°C).

Variation of Refreshment Requirements: From Figure 8 and Table 4, the comparison of cooling requirements for the diverse cases shows that the straw roofing building offers the best performances. It reduces the need for cooling by 37% compared to the slab reference building. As for the terracotta tile roof, the need for cooling is reduced by 16%. On the other hand, the zinc sheet roof increases the cooling requirement by 40%. This can be explained by the high rate of total irradiation on a horizontal plane and the low conductivity of the materials (straw and terracotta) of the roof which reduces the cooling demand. It appeared that the straw roofing increases the energy performance of the building with less need of air conditioning. omenon is observed with the sheet metal roof. Energy Performance of the Edifice: The energy performance of a building is inversely proportional to the need for cooling (Table 5). This performance is obtained by dividing the total annual requirement by the building area (98 m²). Fig. 9 reflects the annual cooling requirement of the reference building for different roofs. Overall, this figure shows that the need for annual cooling of the zinc sheet building is greater than the needs of the concrete roof and straw bale. Evaluation of the Environmental Impact (TEWI): Table 6 presents the results of TEWI calculations for the various roofs. The straw and terracotta roofs have lower environmental impacts compared to the zinc sheet and the concrete slab. The straw and terracotta roofs allow respectively 33% and 15% CO2 emission limits compared to the concrete slab for the building in question.

Conclusion

The work reported herein focuses on the dynamic thermal simulation of the effect of thermal loads by the roof on comfort in a residential building in southern Benin. This study was carried out with the simulation environment TRNSYS 17. To complete this, we chose a reference house built with hollow block walls and slab roofing. Then the inventory of the building reference is made by simulating the evolution of the indoor temperature and energy requirements cooling. Simulation of the same building is done, but this time, replacing the roof (slab) by other variants (zinc sheet, terracotta tiles and straw) to identify the one presenting the best performances. The analysis of the various results has clearly shown that it is possible to reduce the energy consumption of residential buildings by taking roofing materials into consideration starting from the architectural conception. The study proved that the straw roof reduces the need for cooling by 37% compared to the slab reference building. As for the terracotta tile roof, the need for cooling is reduced by 15%. On the other hand, the zinc sheet roof increases the cooling requirement by 40%. The environmental impact in terms of CO2 emissions linked to artificial cooling is equally reduced with straw and terracotta. This work highlights the interest of developing local building materials in order to build more and more ecological buildings (T. Tzoulis and K.J. Kontoleon, 2017).

Competing interests: Authors have declared that no competing interests exist.

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(a) Terracotta tile roof

(b) Zinc sheet roof

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