

## Numerical contribution to the passive ventilation of the bioclimatic housing model

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### ABSTRACT

This study reports a passive ventilation of bioclimatic type housing adapted to Burkina Faso tropical hot and dry climate. The numerical simulation of our bioclimatic housing model led to optimal parameters such as roof inclination  $\alpha = 55^\circ$ , North-South roof orientation, the nature of building materials (BBBPP), the distance  $d = 0.30$  m and the chimney is 0.45 m high, impacting on the rate of air ventilated in the roof and the average temperature of the air in the house. The numerical simulation of these optimal parameters produced an average air temperature in the house of  $27.69^\circ\text{C}$ , and an air flow of  $0.092\text{ m}^3\text{ s}^{-1}$ , flowing by natural convection in the roof. However, the flow still remains fairly low and air temperature within the house remains high as compared the standard ( $24^\circ\text{C}$  to  $27^\circ\text{C}$ ). These results also show that kenaf fibers and cotton wastes may be used as thermal insulator in bioclimatic housing roof. We partly reached our objective initially set, namely modelling and simulating the thermal behavior of a bioclimate thermal model adapted to hot and dry tropical climate. Yet, our study remains a major step in investigating local building materials and finding solutions to the crucial issue of energy consumption by active air processing equipment.

**Key words:** Natural Ventilation, Bioclimatic Roof, Thermal Comfort.

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### Nomenclature

$T$  = Temperature (  $K$  )

$t$  = Time (s)

$S$  = Surface ( $\text{m}^2$ )

$k$  = Thermal conductivity ( $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ )

$Cd$  = Load coefficient

$L$  = Length (  $m$  )

$l$  = Width (  $m$  )

$Ep$  = Thicknesses (  $m$  )

$M$  = The mass of the section (  $kg$  )

$Cp$  = Calorific Capacity (  $J \cdot kg^{-1} \cdot K^{-1}$  )

$hr$  = Radiation transfer coefficient

$hc$  = Transfer coefficients of natural convection (  $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$  )

$d$  = Distance between roof plates (  $m$  )

$Qm$  = Airflow volume ( $m^3 \cdot s^{-1}$ )

$\Delta t$  = Step time (s)

$Nu$  = Nusselt number

$Gr$  = Thermal Grashof number

$Pr$  = Prandtl number

$F$  = Geometric Form factor

$\varepsilon$  = Emissivity

$\alpha$  = Inclination ( $^\circ$ )

$\gamma$  = Roof thermal absorptivity ( $W \cdot m^2$ )

$\eta$  = Density of solar flow harnessed by the absorber ( $W \cdot m^2$ )

$Pu$  = Useful flow density ( $W \cdot m^2$ )

$\phi$  = Solar flux density ( $W \cdot m^2$ )

### Index:

$be$  = External roof

$bi$  = Internal roof

$a$  = Air in the duct

$p$  = Absorber

$is$  = Isolator

$s$  = Exit

$e$  = Entrance

$ke$  = kenaf

$co$  = Cotton

$amb$  = Ambient

$vc$  = The vault of heaven

$pl$  = Ceiling

$amp$  = Air between cotton fiber and ceiling.

## INTRODUCTION

The improvement of thermal comfort in a house can be achieved through passive air conditioning techniques based on natural convection ventilation in houses and through various shading techniques. In Burkina Faso, to face increasing population growth, houses have often been conceived without taking environmental conditions, geographic and climate specificities of the region into account. Houses built according to European comfort standard in terms of temperature and solar radiations are less compatible with the climate and heat in a Sub-Saharan country. Therefore, houses release higher temperatures (thermal discomfort), requiring then, air conditioning to improve thermal comfort for people living there.

A human being can be compared to a thermal engine, which through calorific and evaporation exchange process, ensures its energy equilibrium. The concept of thermal comfort can be characterized, as for an individual, by the satisfaction of environmental thermal conditions. This feeling of thermal comfort is mostly the expression of the overall equilibrium (inputs – loss – energy production) between the individual and its environment [1, 2]. The operation of equipment (heating, ventilating, and Air Conditioning) contributes to increase the consumption in fossil fuel and air pollution. That is why the consumption of energy in public buildings, notably the functioning of air conditioning equipment is estimated at 30 000 MWh/year in Burkina Faso. Since the Kwh average cost is US\$ 0.21, this gives a total cost of US\$ 6,300,000[3].

Therefore, promoting new air conditioning techniques which consume low quantity of energy and improving house energy efficiency are necessary. Passive air conditioning, which consists in reducing the impact of solar radiation on the internal environment through various techniques and taking advantage of the architectural characteristics of houses is very promising. The term bioclimatic refers to few basic principles where the designing and building of houses take the site environment and climate into account to create an internal comfort consistent with the thermal comfort [4, 5, 6].

Our model of bioclimatic housing was designed to trap solar radiation through the roof. It includes local material, Bolle compressed bricks (BTC). The roof is used as a plan captor, with rectangular sloping section, with the inclination angle  $\alpha$  and a conduit where flows the air by natural convection of the area. It was built with compressed mud bricks in the higher part and a transparent substance (Plexiglas), the lower part is the absorber, the insulator is made of kapok tree fiber, agricultural wastes (cotton wastes) and kenaf fiber or Hibiscus Cananbinus [7].

Numerically, we are simulating the performance of this model of bioclimatic roof in Burkina Faso warm and dry tropical climate, through the idea of "typical day" by Lui and Jordan [8, 9]. Temperature distribution of various roof materials, and the air blowing within the roof by natural convection, will allow us upgrading parameters on housing dimension.

#### 4.1 Description of the problem

Our model of bioclimatic roof is in solar captor plan which coverage is made of compressed mud bricks and transparent Plexiglas substance. If we consider a bioclimatic housing as shown in Fig.1, it can be divided into a roof and an enclosure with parallelepiped section. The roof is a rectangular section conduit, with an inclination angle as compared to the horizontal, extending enough to protect the façade and the openings of the vertical faces of the sun flows. It also comprises two parallel plates forming a rectangular section conduct where the internal house air flows by convection. The external face of the roof is built with 0.30 m x 0.10m compressed mud bricks alternating with Plexiglas transparent tiles of the same size. It is equipped with 0.15 m x 0.10 m compressed mud bricks and 0.15 m x 0.10 m Plexiglas substances. This chimney comprises openings through which air flows out of the house toward the ambient environment. The internal face of the roof plaques is made of dark low-thick iron sheet absorber (0.005 m), an insulator with kapok tree fiber (0.10 m), kenaf fiber (0.25 m) and finally a compact layer of cotton waste (0.20 m). As an agricultural country, in Burkina Faso, kenaf fibers from plants and cotton wastes are substantially available and even accessible both in urban and rural area. With the support from the Ministry of Housing and City Planning, we have been able to highlight kenaf fiber to simulate the thermal behavior of our bioclimatic housing model. Also, we requested the collaboration of the National Soil office (BUNASOL) in the choice of the type of clay (Bolle) for our model. The thermal properties of materials included in the roof, supposed constant, are listed in table below.

**Tab.1: Physical properties of roof materials**

Building materials	Mass volume $\rho$ $kg/m^3$	Calorific capacity $C_p$ $J/kg.K$	Absorptivity $\gamma$	Thermal conductivity $K$ $W.m^{-1}K^{-1}$	Emissivity $\epsilon$
Bollé	1800	780	0.485	0.658	0.834
Plexiglas	1200	800	0.128	0.752	0.010
Absorber	2700	920	0.945	180	0.880
Isolator	530	950	0.237	0.016	0.15
Kenaf fiber	50	-	-	0.039	-
Cotton fiber	20	6	-	0.0067	-

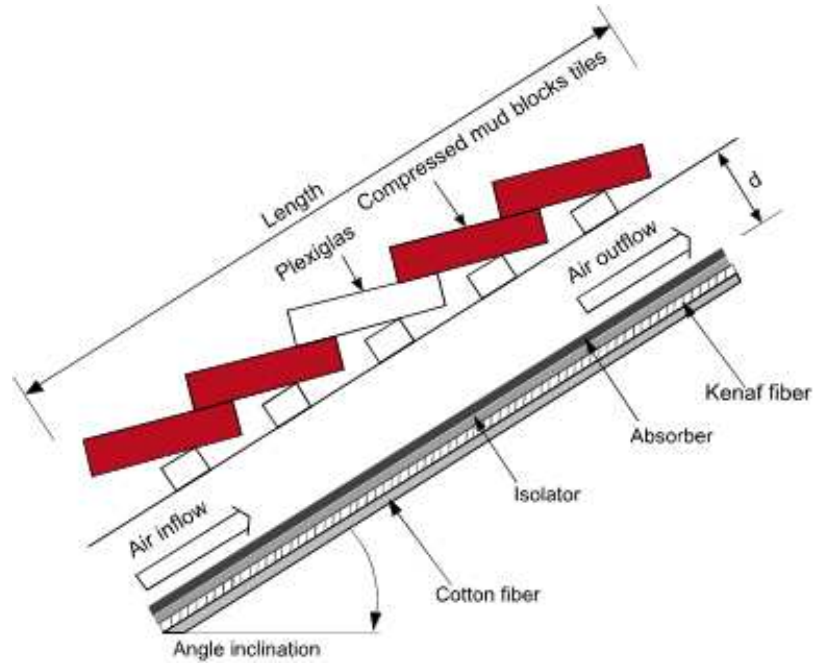
#### 4.2 Roof Operating Principle

Solar flux on the roof is the part captured by compressed mud tiles and the absorber in transparent tiles. Therefore, there are temperature gradients between various materials of the roof and the air causes a natural convection, moving the air between the roof and the house (Fig.1).

The study of this roof can basically be conducted using two methods:

- the first method, the most rigorous, based on the solving of transfer equations through natural convection coupled with the equation of heat transfer by conduction in various materials allows to know the spatio-temporal temperature evolution in various components of the roof (compressed mud tiles, absorber, isolator, kenaf fibers, and cotton fibers) and the speed of the air circulating within the roof.

-the second consists in establishing transfer equation by adapting the analogy between thermal transfers and electric ones. The roof which length  $L= 3$  m is therefore divided into 19 fictive slides perpendicular to the airflow. The solving of equations allows therefore following the evolution over time of temperature distributions of the various components based on the calculation of the coefficients of heat transfer by natural convection.



**Fig.1: Physical Model of the Roof**

**4.3 Simplifying Assumptions:**

- 1: transfers are unidirectional.
- 2: air thermal inertia is trivial.
- 3: air is well transparent during solar radiation.
- 4: the roof and house are not the seat of any mass transfer.
- 5: materials are treated as gray bodies.
- 6: the sky operates like a blackbody.
- 7: atmospheric diffuse radiation is isotropic.
- 8: false ceiling in kenaf tow.

**4.4 Mathematical Formulation**

The method consists in cutting the roof into fictive slices following the airflow. To write the thermal results in each slice, we use analogies between heat transfers and electrical transfers. By applying Ohm’s law to each slice of the roof, we get the following thermal results:

External

$$\frac{M_{be} CP_{be}}{S} \frac{\partial T_{be}}{\partial t} = \gamma_{be} \eta_{be} + \frac{k_{be}}{Ep_{be}} (T_{bi} - T_{be}) + hr_{be} (T_{vc} - T_{be}) + hc_1 (T_{amb} - T_{be}) + hr_{amb} (T_{amb} - T_{be}) \quad (1)$$

Internal

$$\frac{M_{bi} CP_{bi}}{S} \frac{\partial T_{bi}}{\partial t} = \frac{k_{bi}}{Ep_{bi}} (T_{be} - T_{bi}) + hc_2 (T_a - T_{bi}) + hr_{p \rightarrow bi} (T_p - T_{bi}) \quad (2)$$

The air in the canal

$$\frac{M_a CP_a}{S} \frac{\partial T_a}{\partial t} = hc_3 (T_p - T_a) + hc_3 (T_{bi} - T_a) + Pu \quad (3)$$

Absorber

$$\frac{M_p CP_p}{S} \frac{\partial T_p}{\partial t} = \varepsilon \gamma_p \eta_p + \frac{k_p}{Ep_p} (T_p - T_{is}) + hc_4 (T_a - T_p) + hr_{p \rightarrow vc} (T_{vc} - T_p) + \sum_{i=1}^3 hr_{i \rightarrow t_p} F_{i,t_p} (T_i - T_i) + \Phi \quad (4)$$

Isolator

$$\frac{M_{is} CP_{is}}{S} \frac{\partial T_{is}}{\partial t} = \frac{k_{is}}{Ep_{is}} (T_p - T_{is}) + \sum_{i=1}^2 hr_{i \rightarrow pl} F_{i,pl} (T_i - T_{is}) \tag{5}$$

Kenaf Fiber

$$\frac{M_{ke} CP_{ke}}{S} \frac{\partial T_{ke}}{\partial t} = \frac{k_{ke}}{Ep_{ke}} (T_{is} - T_{ke}) + \sum_{i=1}^2 hr_{i \rightarrow pl} F_{i,pl} (T_i - T_{ke}) \tag{6}$$

Cotton Fiber

$$\frac{M_{co} CP_{co}}{S} \frac{\partial T_{co}}{\partial t} = \frac{k_{co}}{Ep_{co}} (T_{is} - T_{co}) + hc_5 (T_{co} - T_{amp}) + \sum_{i=1}^2 hr_{i \rightarrow pl} F_{i,pl} (T_i - T_{co}) \tag{7}$$

**4.5 Airflow in the roof:**

The airflow volume  $Q_m$  ( $m^3 / s$ ) is obtained by natural convection in the duct using the expression by Bansal and al [10] :

$$Q_m = Cd.S \left[ g.L.\sin \alpha \left( \frac{T_s - T_e}{T_e} \right) \right]^{1/2} \tag{8}$$

**4.6 Transfer coefficient by Natural Convection:**

This is a summary of few semi-empirical correlations on the convective exchange used to calculate exchange coefficients by natural convection. The exchange of heat between the external side of the roof and the air is basically made by wind. Heat transfer coefficient  $hc_1$  therefore derived from Mc Adam relation [11]

$$hc_1 = 5.7 + 3.8 V \tag{9}$$

Where:  $v$  is wind speed.

**4.7 Open parallelepiped Enclosure:**

Since the roof has been compared to an open rectangular area, heat transfer coefficient ( $hc_2=hc_3$ ) between the inclined plate compared to the vertical and the air circulating in the duct is inferred from the relation proposed by J. Khedari and al [12]. For any Grashof's thermal number ranging between  $2.1 \cdot 10^5$  and  $1.1 \cdot 10^7$  and for the formal relation  $H / L \geq 10$ , with  $Pr \approx 0.7$ , local Nusselt is:

$$Nu_L = 1 + \left[ 0.071 (Gr.Pr)^{1/3} \left( \frac{H}{L} \right)^{-1/9} - 1 \right] \sin \alpha \tag{10}$$

and  $hc_2 = hc_3 = \frac{Nu_L.k}{L}$  (11)

Convection-based heat transfer coefficients between the internal isolator and compressed air have been calculated based on the following formula:

$$hc_4 = hc_5 = 1.42 \left[ \frac{\sin \alpha (T_{co} - T_{amp})}{L} \right]^{0.25} \tag{12}$$

**5. Computational Procedure**

For a time frame  $\Delta t$  between  $t_j$  and  $t_{j+ \Delta t}$ , we describe all the physical system of the first slice to the last spatial section. Solving the equations of thermal equilibrium in each section gives temperature distribution. These same operations are repeated till time  $t=20s$  elapses. Equations (1-7) have been discredited using an implicit finite difference method. This method is based on Taylor's series development and allows transforming these equations into a system of algebraic equations which solving requires an iterative calculation to determine physical quantities at a given time according to unknown variables at this same time and known variables at the previous time. At the initial time  $t_0$ , temperatures of all areas are supposed equal to the ambient temperature. Various heat transfer coefficients have been calculated at time  $t_0+ \Delta t$ , by given an arbitrary value corresponding to the ambient

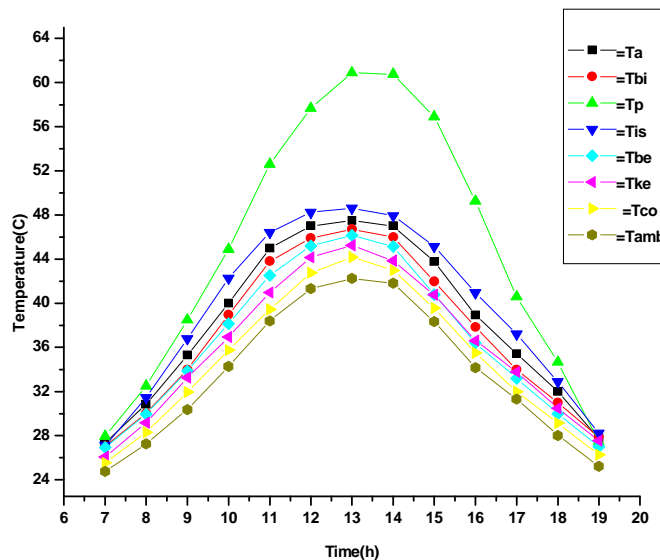
temperature to temperatures in various areas of the roof. The algebraic equation system is then solved using “Diabolo Sablier” method. The calculation leads to new values of temperatures that compared with arbitrary values. If the difference is higher than the desired accuracy, i.e. 0.05, temperature values calculated replace the arbitrary values and the calculation procedure is resumed until getting the desired accuracy. Air temperature in this section is then calculated and considered as equal to air temperature when entering into the next section. To start calculations, it is necessary to know the airflow conveyed by natural convection throughout the roof. This flow is proportional to the difference in temperature of the air between the entry and outflow from the roof considered as a duct. Also, it is necessary to give to this temperature an arbitrary value to determine the airflow going through the duct based on the correlation and therefore solve the equations. So, the temperature of the air getting out of the roof is compared with the arbitrary value given to it for the calculation of the airflow. If the gap is less than the expected accuracy, i.e. 0.05, calculations are incremented to a time frame, otherwise the outgoing temperature calculated replaces the arbitrary value and the solving of equations is resumed until the accuracy expected is reached.

**RESULTS AND DISCUSSION**

Our calculations were made using metrological data on the Ouagadougou City, with the idea of typical day celebrated on April 27, 2010. This period corresponds to the dry season characterized by air temperatures and high heat flows.

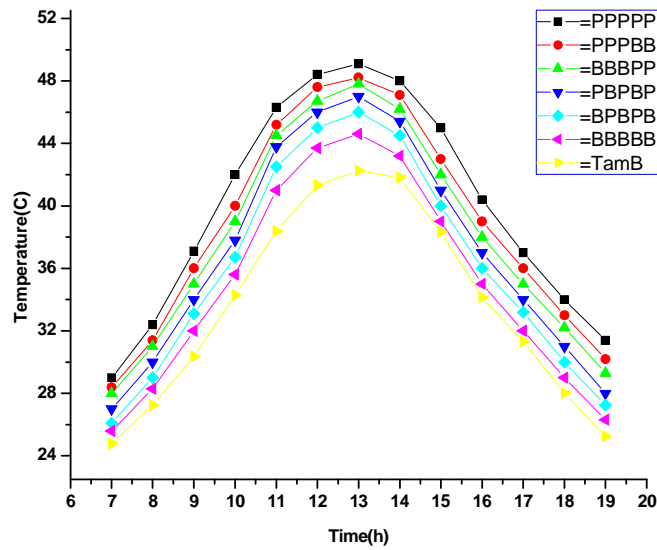
Knowing the spatio-temporal temperature distribution of all the roof materials and the air flow provided by natural convection seems necessary to calculate the optimal dimensions of our model of bioclimatic roof.

Therefore, we studied the impact of its sloping ( $\alpha$ ) compared to the horizontal, with values comprised between  $50^\circ$  and  $75^\circ$  and its geographic orientation on air temperature distribution in the roof and within the house. Accordingly, the increase in the sloping angle of the roof leads to the decrease in the air average temperature. Indeed, solar flow captured by the roof and therefore, the heat flow transferred by conduction to the various components of the roof decreases with the inclination angle. However, air flow within the roof increases as the inclination does. For  $\alpha < 50$ , the flow captured may reach  $900\text{W/m}^2$ ; this enables conduction-based exchanges between the various components of the lower part of the roof. For  $\alpha = 55$ , the flow captured is around  $550\text{W/m}^2$ . We chose this value because beyond this, it is hardly possible in practice.



**Fig.2: Evolution of roof materials surface temperature over time.**

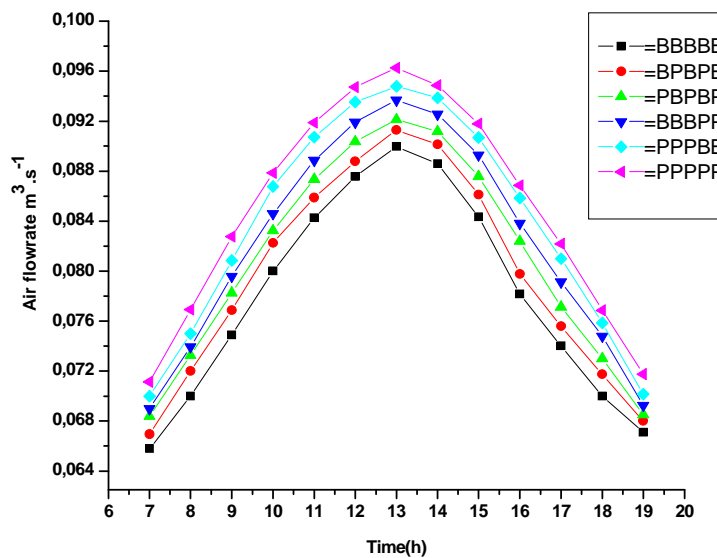
When comparing air and various materials temperature profiles (Fig.2), it can be noticed that air temperature ( $T_a$ ) exceeds those of the other roofing materials, except that of the absorber ( $T_p$ ). This may seem contrary to the idea sought in the concept of passive cooling. But this can be explained by the presence of Plexiglas tiles leading to the increase in solar flow captured by the elements of the lower part of the roof, together with the increase in the intensity of the radiation exchanges within the roof. Also, ( $T_{ke}$ ) and ( $T_{co}$ ) show that plant fibers significantly reduce conduction transfers.



**Fig.3: Evolution of airflow temperature within the roof over time.**

We analyze the impact of the types of compressed mud tiles (B) and Plexiglas tiles (P) on the distribution of temperatures and on the airflow within the roof. Temperature and airflow are all the higher when the surface of the roof, transparent to radiation, is big (Fig.3). Indeed, solar flux produced by this roof is partly absorbed by various enclosures facing this roof. Then, there is an increase in conduction-based transfers through various materials and by convection between the air and the other plates forming the roof.

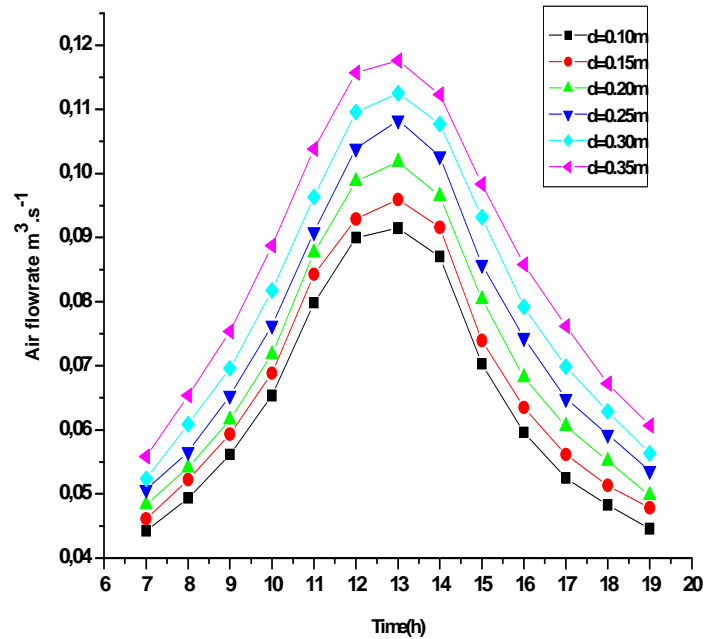
To follow the evolution of the airflow over time and find an optimal flux, several types of roof were considered. This concerns the upper side of the roof in contact with the surrounding environment. As illustrated by Fig.4, if this part is completely covered with compressed mud tiles or Bollé (BBBBB), there is a low airflow  $Q_m = 0.083 \text{ m}^3 \text{ s}^{-1}$ , and temperature is  $44.6^\circ\text{C}$ ; hence the thermal discomfort within the house. But in a roof fully covered with Plexiglas tiles (PPPPP), the average airflow may reach  $0.11 \text{ m}^3 \text{ s}^{-1}$  and air temperature,  $49.17^\circ\text{C}$ . However, with high material costs, we did not opt for it in practice. ((BBBPP) type coverage gives airflow accounting for  $0.092 \text{ m}^3 \text{ s}^{-1}$  and temperature of  $46.7^\circ\text{C}$ .



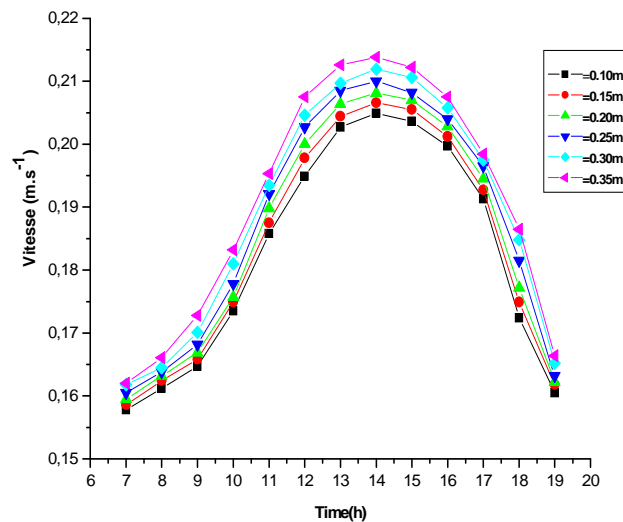
**Fig.4: Impact of roof materials over time on airflow volume circulating in the roof.**

Also, it is necessary to determine the optimal distance (d) between two plates of the roof for maximum airflow. It can be noticed that  $Q_m$  increases significantly with d in the roof (Fig.5). However, the average temperature of

various roof materials, and notably air temperature remains less sensitive to the variation of (d). The distance also influences the velocity of air in the roof (Fig.6).



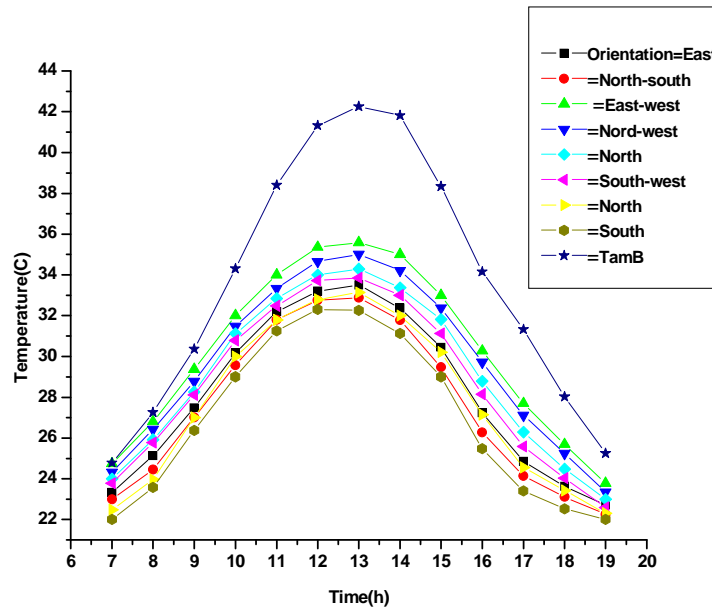
**Fig.5: Impact over time of the distance between both plates making the roof on the airflow volume.**



**Fig. 6: Impact over time of the distance between both plates making the roof on the air velocity.**

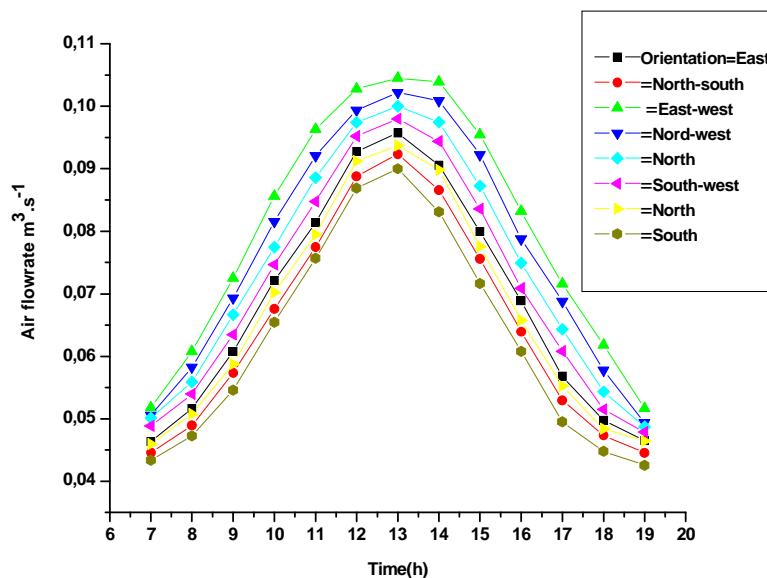
Modeling and simulating the operation of the bioclimatic roof have shown that the airflow generated by natural convection is higher for an angle of inclination of  $\alpha=55^\circ$ , and the distance between both plates of the roof (d=0.30 m) increases. Moreover, the temperature of the air flowing in the roof decreases when the angle of inclination of the roof increases, for a better positioning.



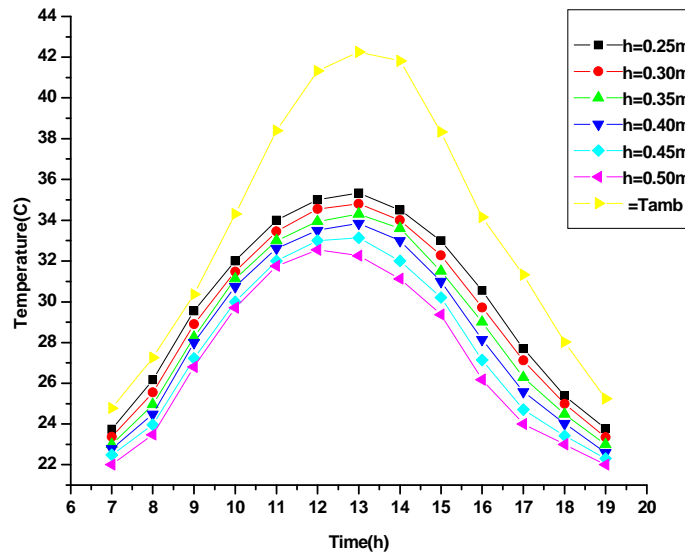


**Fig.7: Evolution over time of air temperature within various positions of the house.**

Curves in Fig.7 and Fig.8 show that the position of the external side of the roof, because the intensity of heat flows in these various items, impacts on the airflow. So, for a roof displayed North-South, sun flux captured for this roof is low. Therefore, the temperature of various materials within the house and accordingly, that of the air is less than that obtained with the other roof positions. A comparison between the temporal distributions of the average air temperatures within the house gives 27.69°C and the airflow is 0.092 m<sup>3</sup> s<sup>-1</sup> within the roof, while the optimal angle of inclination is 55°, showing that the North-South direction leads to a significant decrease in air temperature within the house compared to that of the ambient.



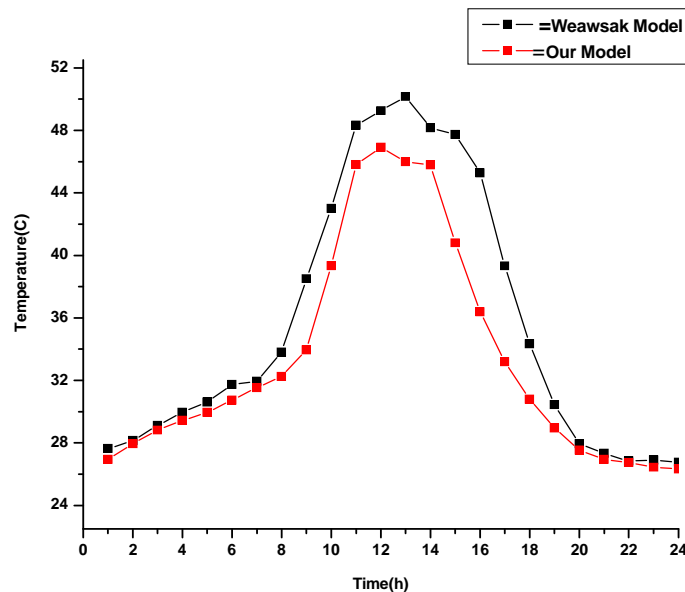
**Fig.8: Impact of roof position on the airflow volume through the roof.**



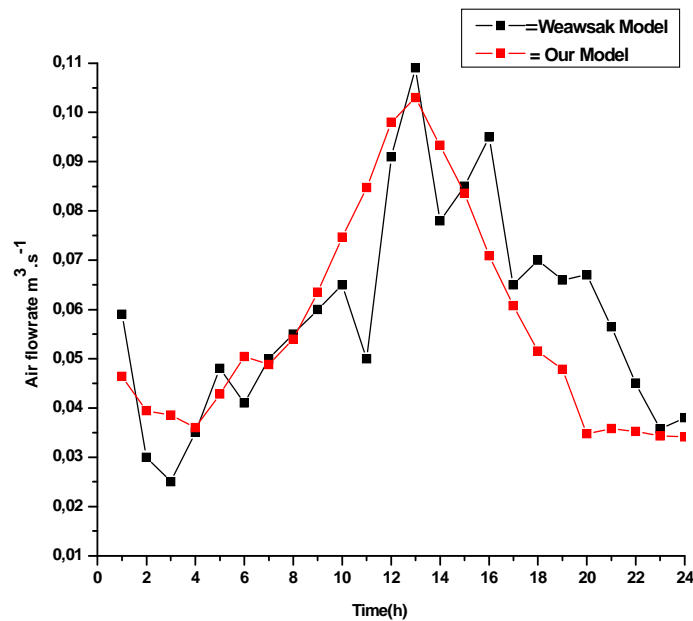
**Fig.9: Impact of the heights chimney over time of the air temperature within the house.**

Curves in Fig.9 show that the level of the roof chimney impacts on air temperature within the house as well as the flow of the air in the roof. By comparing temperature profiles at various heights (h) of the chimney, it can be noticed that when h=0.45 m, the average air temperature within the house is 27.69°C, while airflow is 0.092 m<sup>3</sup> s<sup>-1</sup> in the roof. However, air speed in the chimney exceeds 0.2 m s<sup>-1</sup>, which is due to the impact of the chimney (natural blowing or static depression due to the chimney), explaining a fairly significant renewal of the air in the roof and that within the house.

Additionally, other factors influence the atmosphere within the house, including the thickness of compressed mud walls (Bollé) of 0.30 m, and window size of 0.60 m. To validate our numerical results, we compared them with those obtained by J. Waewsak [13] on a similar roof in Thailand (Fig.10 and Fig.11). Indeed, the maximal relative gap for temperature is about 8% and 10% for the airflow. These gaps are mainly due to the difference in roof materials, notably the presence of gypsum plate in the lower part of the roof. Also, it is worth noting the difference between meteorological data for humid tropical climate and dry tropical climate.



**Fig.10: Validating roof air temperatures.**



**Fig.11 validating rood airflow.**

In addition to the temperature of the house and the airflow in the roof, we suggested the lack of physical activity for those living in it and the local mode of dressing which is very light in April, and finally the age of people living there ranging between 25 and 57 years. Both parameters comply with the thermal Comfort in buildings [14].

#### Acknowledgement

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#### CONCLUSION

At the end of this study on bioclimatic housing, we show that several conditions impact on the thermal comfort of this model, including roof inclination angle, North-South orientation of the roof, the nature of materials making the higher part the roof (BBBPP), the distance  $d=0.30$  m, and the chimney height ( $h=0.45$  m). They impact on the ventilated air flow in the roof and the average air temperature in the house. The digital simulation of these optimal parameters gave an average  $27.69^{\circ}\text{C}$  air temperature in the house and  $0.092\text{ m}^2\text{s}^{-1}$  air circulating by natural convection in the roof. Yet, the flow still remains fairly low and air temperature within the house remains high, with the slightest difference compared to B. Givon standard norm ( $24^{\circ}\text{C}$  and  $27^{\circ}\text{C}$ ) for dry and hot regions [15,16]. We partly reached our objective set at the beginning, namely modeling and simulating the thermal behavior of a bioclimatic housing model adapted to dry and hot tropical climate. It can be noted also that kenaf fibers significantly reduce heat transfers by conduction in the lower walls of the roof. However, our study constitutes a key step in investigating local materials to find solutions to the tricky energy consumption issue by active air treatment equipment.

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