Research Paper

Thermal Analysis of the Walls of a Bioclimatic Building in Earth : Measurement of Temperatures of External and Internal Surfaces

KABORE Arouna[1], KABORE Hermann[1], ZOMA Vincent[1], SANDWIDI Sayouba[2], PALM Kalifa[3]

[1]Laboratoire des Energies Thermiques et Renouvelables (LETRE), Université Joseph KI-ZERBO, 03 BP 7021 Ouagadougou 03, Burkina Faso.
[2]Laboratoire de Physique et Chimie de l'Environnement, Université Joseph KI-ZERBO, 03 7021 Ouaga 03, Burkina Faso
[3]Laboratoire des Systèmes d'Energie Renouvelable et Environnement, Institut de Recherche en Sciences Appliquées et Technologies (IRSAT), Centre National de la Recherche Scientifique et Technologique (CNRST), 03 BP 7047 Ouagadougou 03, Burkina Faso.

Corresponding Author: KABORE Arouna

ABSTRACT

The thermal performance of a building depends on the materials that make up its envelope. The envelope of most buildings in the Sahelian zone is composed of modern materials such as cement blocks, concrete, corrugated sheet metal, etc. These materials, for the most part, have high thermal conductivities and generate high heat transmission to the interior of buildings, resulting in discomfort. Most of these materials have high thermal conductivities, resulting in high heat transfer to the interior of buildings, discomfort and increased cooling load requirements. The need to find solutions to reduce cooling loads is obvious. This study is a continuation of the experimental study of the thermal performance of an earthen building with a domed roof. The aim is to study the thermal performance of the building's walls and domed roof. To do so, we analyzed the temperatures of the external and internal surfaces of the walls and of a few points of the dome roof obtained through a measurement campaign during a warm period. The results show that the building's domed roof has an average damping of 14.45°C, an average thermal phase shift of 6 h 23 min and a damping factor of 12.15%. The walls have an average damping of 7.54°C, an average thermal phase shift of 7 h 01 min and a damping factor of 9.7%. These values show that the building's walls and roof have good thermal inertia and confirm that earth-based materials are better than materials such as breeze-block. Buildings constructed with earthen materials therefore make a significant contribution to reducing inward heat transfer in the Sahelian zone.

Key words : Thermal performance ; thermal conductivity; average damping ; thermal phase shift ; damping factor ; thermal inertia.

I. INTRODUCTION

Sahelian countries are faced with an increasing population in urban areas. This increase is due partly to a high birth rate and partly to the rural exodus in search of better living conditions. To accommodate these populations, they use all kinds of buildings, most of which overheat during periods of high heat. To cope with this overheating, they use mechanical cooling systems, which increase their electricity consumption and consequently their electricity bills. The

building sector is the main consumer of electricity, accounting for around 55% of global consumption, and in particular that of African countries [1]. Half of the electricity produced in African countries is consumed in buildings. Solutions must therefore be found to reduce this excessive consumption. Bioclimatic construction could be an alternative to the majority of current buildings, in particular the use of solid materials such as earth in construction. Several studies have shown that local earth-based materials can help improve thermal comfort and reduce energy consumption. [2], [3], [4], [5] have shown in their work that the air temperature in the internal environment of buildings constructed with adobe bricks is stable in relation to the external air temperature. They showed that this stability can be explained by the thermal inertia of the adobe bricks that make up the walls of these buildings. [6] have shown in their work that walls built with adobe bricks have damping factors of less than 50%, giving them good thermal inertia. Following this logic, a preliminary study was carried out by [7]. They studied variations in internal air temperatures in an earthen building with a domed roof. These temperatures, obtained through a campaign of in situ measurements over three periods typical of Burkina Faso's climate, showed that the building was able to regulate internal temperature fluctuations, reducing the external temperature by an average of 10.81°C over the three periods. The study also showed that during the hot period, the external air temperature was reduced by an average of 10.5°C. The study is limited in that it does not allow us to see
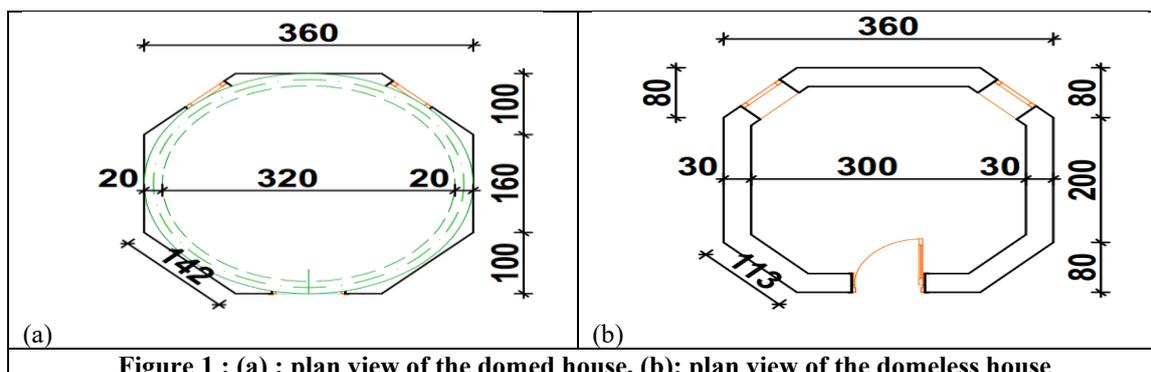
the thermal behavior of the dome walls and roof.

The present study focuses on variations in the external and internal face temperatures of the domed walls and roof, with the aim of highlighting the thermal performance of the walls and roof during the warm period.
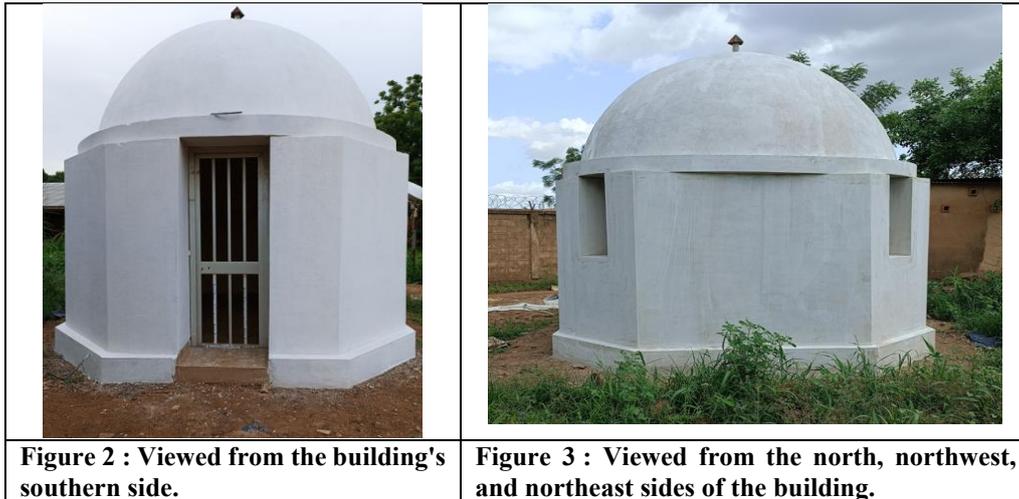
II. MATERIALS AND METHODS
II.1. Experimental set-up and measurement protocol
II.1.1. Description of the site and experimental set-up

The bioclimatic building is located at the Institut de Recherche en Sciences Appliquées et Technologiques (IRSAT) in Ouagadougou, more precisely in the Kossodo industrial zone, a section of the Centre National de Recherche Scientifique et Technologique (CNRST). It is built according to the Nubian vault construction technique, using modern buildings techniques and modern materials such as cement, plastic sheeting, paint, etc. Local materials are used for 90% of the construction. Local materials are used for 90% and modern materials for 10%. The aim is to ensure the durability of the building's structure. The walls are octagonal and the roof is domed (a semi-hemispherical vault). The interior volume of the habitat is 20.66 m3, i.e. 6.66 m3 for the interior space of the dome and 14 m3 for the interior space of the walls. Figure 1 shows the floor plan of the building, a plan view of the building with dome and a plan view of the house without dome. Figures 2 and 3 shows a view of the south side of the building, respectively, and a view of the north, northwest and northeast sides of the building.

(a)   (b)

Figure 1 : (a) : plan view of the domed house, (b): plan view of the domeless house

| Figure 2 : Viewed from the building's southern side. | Figure 3 : Viewed from the north, northwest, and northeast sides of the building. |

II.1.2. Building materials

The walls are made of adobe bricks, 40 cm*13 cm*13 cm in size, mostly composed of clay and Kenaf fibers.

The roof is a dome, 19 cm thick, with inside and outside diameters of 3.6 m and 3.22 m respectively. The roof is made of adobe bricks composed of clay and Kenaf fiber. Brick dimensions are 23 cm*16 cm*5 cm.

The door and windows are single-glazed. The door is 80 cm*220 cm and the windows are 80 cm*100 cm.

The floor is made of clay and a thin layer of cement, on which 2 cm thick tiles are laid.

Table 1 shows the thermophysical properties of the two types of clay bricks with Kenaf fibers, as determined by KD2-Pro characterization.

Table 1: Thermophysical properties of adobe bricks

	Thermal conductivity $(W/m.K)$	Thermal capacity $(J/kg.K)$	Density $(kg//m^3)$
Large size Adobe	0,447	791	1923,08
Adobe small size	0,416	1169	2073,58

In addition to the above bio-sourced materials, other materials were used in the construction of the bioclimatic building.

These materials and their thermophysical properties are detailed in Table 2 :

Table 2 : Thermophysical properties of materials used in building construction

	Thermal conductivity $(W/m.K)$	Thermal capacity $(J/kg.K)$	Density $(kg//m^3)$
Sand + cement coating [6]	0,87	105	2200
Clay earth coating [6]	0,8	2062,81	1669,73
Cement mortar [8]	1,75	663	2100
Bitumen for waterproofing [9]	0,5	1000	1700
Single glazing [8]	1,15	1000	840
Tile [10]	1,15	700	1800

II.2. Instrumentation
II.2.1. Temperature measurement
Internal wall, external wall, external ambient air and internal ambient temperatures are measured using type K and type J

thermocouples with accuracies of 1.6°C and 1.7°C respectively.

II.2.2. Internal and external relative humidity measurement

Data on the relative humidity of indoor air and outdoor air are collected by two MSR 320669 humidity measurement modules. The two moisture meters are stand-alone, independent of each other, and enable air humidity to be recorded. One is placed in the indoor environment to measure indoor air humidity, and the other in the outdoor environment to measure outdoor air humidity.

II.2.3. Measurement of solar radiation from the site

A solarimeter is used to measure sunshine levels at the site. It is placed outside the home, on a flat surface inclined at an angle of 15° and facing south.

II.3. Méthode de traitement des données

The thermocouples are connected to a Datalogger, which is set up for the different types of thermocouple, type K or J. One channel of the Midi-Logger GL220 Datalogger is reserved for connection to the solarimeter. The Solarimeter, with a sensitivity of 72 mV for 1000 W/m2, is placed on a flat device, inclined at an angle of 15° to the horizontal and facing south. A time step of 5 min is chosen for the measurements. The Dataloggers are powered by a photovoltaic system, comprising a photovoltaic plate, a battery and a regulator, and we launched all the temperature and humidity data acquisition modules simultaneously to ensure that the various data were taken at the same times. Measurements took place from 04/23/2024 to 05/05/2024.

At the end of the measurements, the data were retrieved in CSV format on USB sticks, pre-processed in Excel and finally processed with Origin Pro software.

II.4. Characterizing the thermal inertia of building walls

Thermal inertia is a very difficult concept to grasp. It can be defined as the resistance to a change in a building's internal temperature [11]. Resistance to changes in a building's internal temperature is its ability to store heat received during the day in its envelope and release it to the external environment at night when the external temperature is low. To assess a building's thermal performance, it is possible to characterize its thermal inertia. Characterizing inertia involves assessing the thermal phase shift and damping factor.

II.4.1. Thermal phase shifting

The thermal phase shift of a material, wall or building is determined from the temperatures of the external and internal environments. The thermal phase shift is the time required for the inside temperature to reach its maximum from the moment the outside temperature reaches its maximum. The thermal phase shift is then determined by the difference between the times of the external and internal temperature peaks, and is given by equation I.10 :

$$\phi(h) = t_{Tin,\max} - t_{Tex,\max} \qquad (1)$$

With : $\phi(h)$: thermal phase shift in hours (h) ; $t_{Tin,\max}$ et $t_{Tex,\max}$: are respectively the dates when the internal and external temperatures reach their maximum, and are expressed in hours (h). The higher the value of the thermal phase shift, the more the building delays the transmission of the external temperature peak to the building interior. A high delay means that the internal temperature will be impacted when the external temperature decreases or reaches its minimum value. This impact will then be less significant.

II.4.2. Damping factor

The damping factor is the ratio of the amplitude of the internal temperature to the external temperature. It then represents the percentage of heat reached on the external surface that is transferred to the internal surface of the building envelope. The damping factor can be evaluated by equation I.11 :

$$f = \frac{\Delta T_{in}}{\Delta T_{ex}} = \frac{T_{in,\max} - T_{in,\min}}{T_{ex,\max} - T_{ex,\min}} \qquad (2)$$

With f damping factor in (%), $T_{in,\min}$ and $T_{ex,\min}$: minimum external and internal

temperatures in °C; $T_{ex,max}$ and $T_{in,max}$: maximum external and internal temperatures in °C.

The lower the value, the better the building's ability to absorb external thermal loads and attenuate internal temperature fluctuations. It therefore provides information on the building's ability to stabilize internal temperature.

A high value for the thermal phase shift and a low value for the damping factor indicate that a building has good thermal inertia.

II.5. Local weather conditions

Figure 4 shows the evolution of solar radiation at the site from 04/23/2024 to 05/05/2024 (figure 4.a) and on 04/25/2024 (figure 4.b). A virtually constant trend can be observed throughout the measurement period. Maximums valus range from 800 W/m² to 1080 W/m². The peaks vary from one day to the next, due to the regular presence of cloud cover at this time of year and the frequent presence of dust.

**Figure 4 : (a) Global solar radiation of the site from 23/04/2024 to 05/05/2024
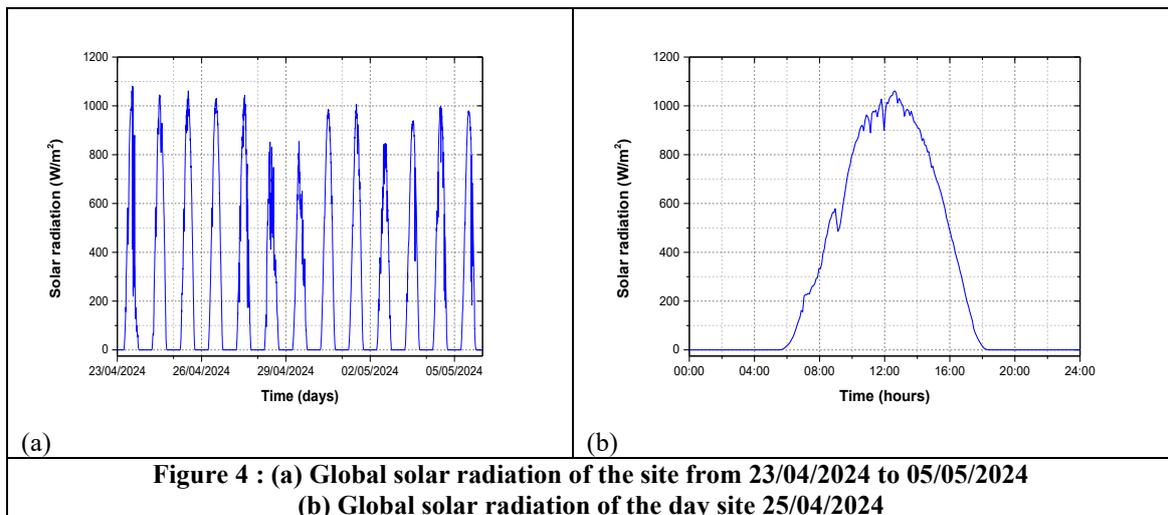(b) Global solar radiation of the day site 25/04/2024**

Figure 5 shows air temperature trends in the outdoor environment from 04/23/2024 to 05/05/2024. It can be seen that the temperature varies according to climatic conditions, and more particularly solar radiation, with values ranging from 21°C to 48.7°C. Maximum values vary between 42.3°C and 48.7°C, and are reached between 12 h 30 min and 14 h 47 min. Minimum values ranged from 21°C to 32.3°C, and were reached between 5 h and 6 h 10 min. The average air temperature in the outdoor environment is 35.72°C. This is the hottest period of the year, which explains the very high temperatures.

Figure 5 : (a) : Evolution of the temperature of the outside air from 23/04/2024 to 05/05/2024 ; (b) : temperature of the outside air from 25/04/2024
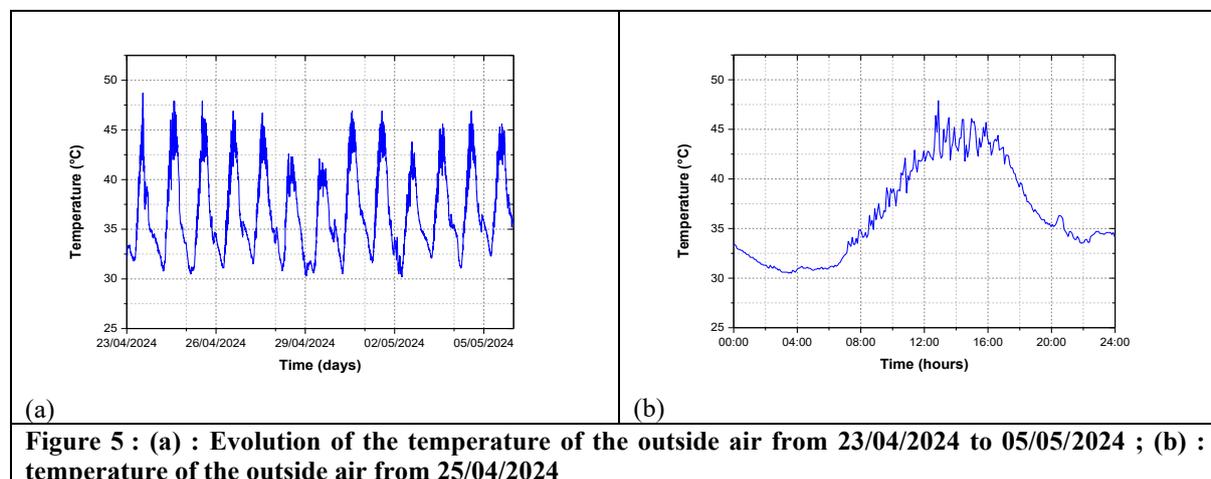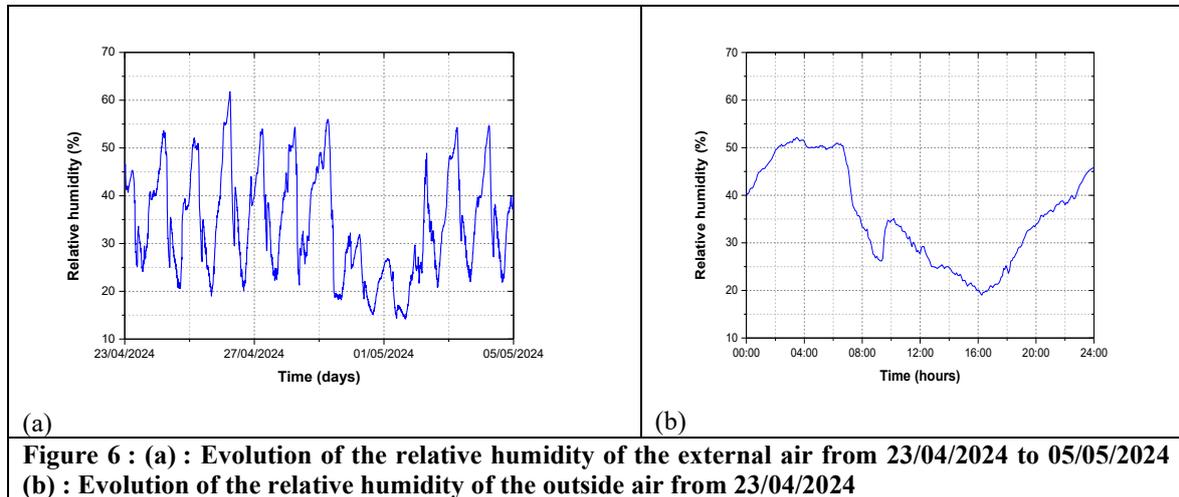
Figure 6 shows the relative humidity profile of the ambient air for the period from 04/25/2024 to 05/05/2024 (figure 6.a) and the humidity profile for the day of 05/01/2024 (figure 6.b). Maximum relative humidity values range from 26% to 62%. Minimums valus range from 15% to 25%.

We can see that changes in the relative humidity of the ambient air over a 24-hour period (figure 6.b) are dependent on changes in ambient air temperature. The higher the water vapour content, the lower the air temperature.

Figure 6 : (a) : Evolution of the relative humidity of the external air from 23/04/2024 to 05/05/2024 (b) : Evolution of the relative humidity of the outside air from 23/04/2024

III. RESULTS AND DISCUSSION

The experimental data processed in this work are for the period from 04/23/2024 to 05/05/2024. The results presented concern the temperatures of the external and internal faces of the building walls and of a few points located on the external and internal surfaces of the domed roof.

III.1. Temperatures at several points on the outer and inner surfaces of the domed roof

Figures 7.a to 7.d show the temperatures of some points on the outer and inner surfaces of the dome. We can see that the temperatures of the points on the outer surface of the dome vary considerably, in contrast to the temperatures on the inner surface. This is because the outer surface receives direct and constant solar radiation during the day, resulting in instantaneous variations in the temperatures of the various points. The highest temperature values are recorded on the western point of the dome's outer surface, with maximum values of up to 58.3°C. Temperatures are higher at this point than at other points on the external surface, as it is the point most exposed to solar radiation.

(c)   (d)

Figure 7 : Temporal variations of temperatures at some points in the external and internal surfaces of the dome roof
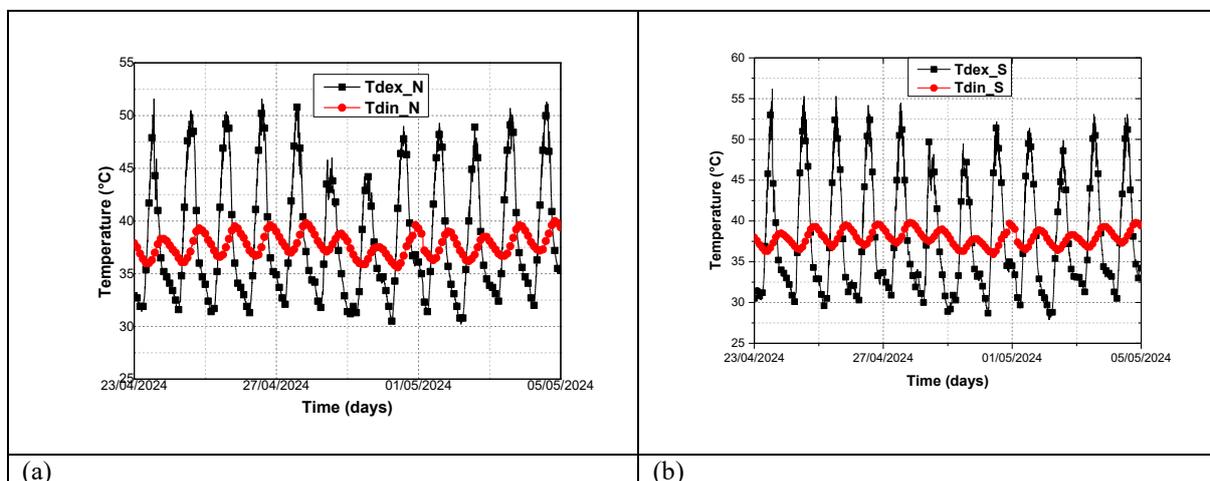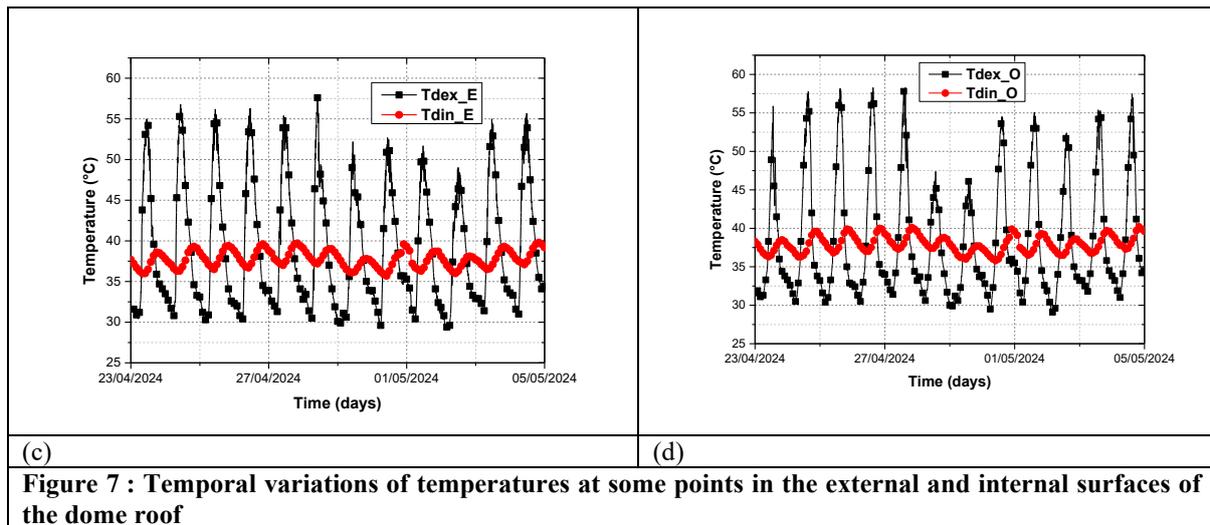
To better appreciate the thermal performance of the roof, we present in Table 3 the average maximum temperatures, average damping, average thermal phase shifts and average damping factors of the points on the outer and inner faces of the dome.

Table 3 : Maximum average temperature, average damping and mean thermal phase shift

	Max. (°C)		Amortization (°C)	Thermal phase shift (h)	Damping factor (%)
	External	**Internal**			
P_{Nex} (45°)	49,43	39,23	10,17	6 h 9 min	13,85
P_{Sex} (45°)	52,75	39,38	13,38	6 h 24 min	11,22
P_{Eex} (45°)	56,23	39,3	16,9	7 h 42 min	11,41
P_{Oex} (45°)	57,11	39,81	17,37	5 h 17 min	12,15
Average	53,88	39,43	14,45	6 h 23 min	12,15

We find that the average damping of the temperature peaks of the points considered on the outer face of the dome is 14.45°C, the average thermal phase shift between the temperature peaks of the points on the outer face and between the temperature peaks on the inner face of the dome is 6 h 23 min, and the average damping factor is 12.25%. This average thermal phase shift (6 h 23 min) is low compared with the heat diffusion time through the bricks used to build the dome (33h). This probably means that the internal surface of the dome is strongly impacted by convection with internal ambient air and air infiltration through the chimney installed at the top of the roof.

The average values for damping (14.45°C), thermal phase shift (6 h 23 min) and damping factor (12.25%) are better than those of corrugated or galvanized roofs, which instantly transmit the heat received to the interior of the home. In this way, the domed roof helps to significantly reduce the transmission of heat to the interior. This performance is due to the shape of the dome roof, the thickness of the dome and the thermophysical properties of the adobe used to build the dome, which gives the roof good thermal inertia.

III.2. Presentation of external and internal wall surface temperatures

Figures 8.a to 8.h show the temperature profiles of the outer and inner surfaces of the building walls. Temperatures on the external surfaces of the building's walls reach maximum values of up to 53.2°C. The highest temperature values are found on the external surfaces of the northwest, east and west walls, with values of 53.2°C, 51.2°C and 52.2°C respectively. As can be seen from the graphs, the temperatures recorded on the external surfaces are highly damped by the building's walls, and the temperatures on the internal faces of the walls are more stable than those on the external faces.
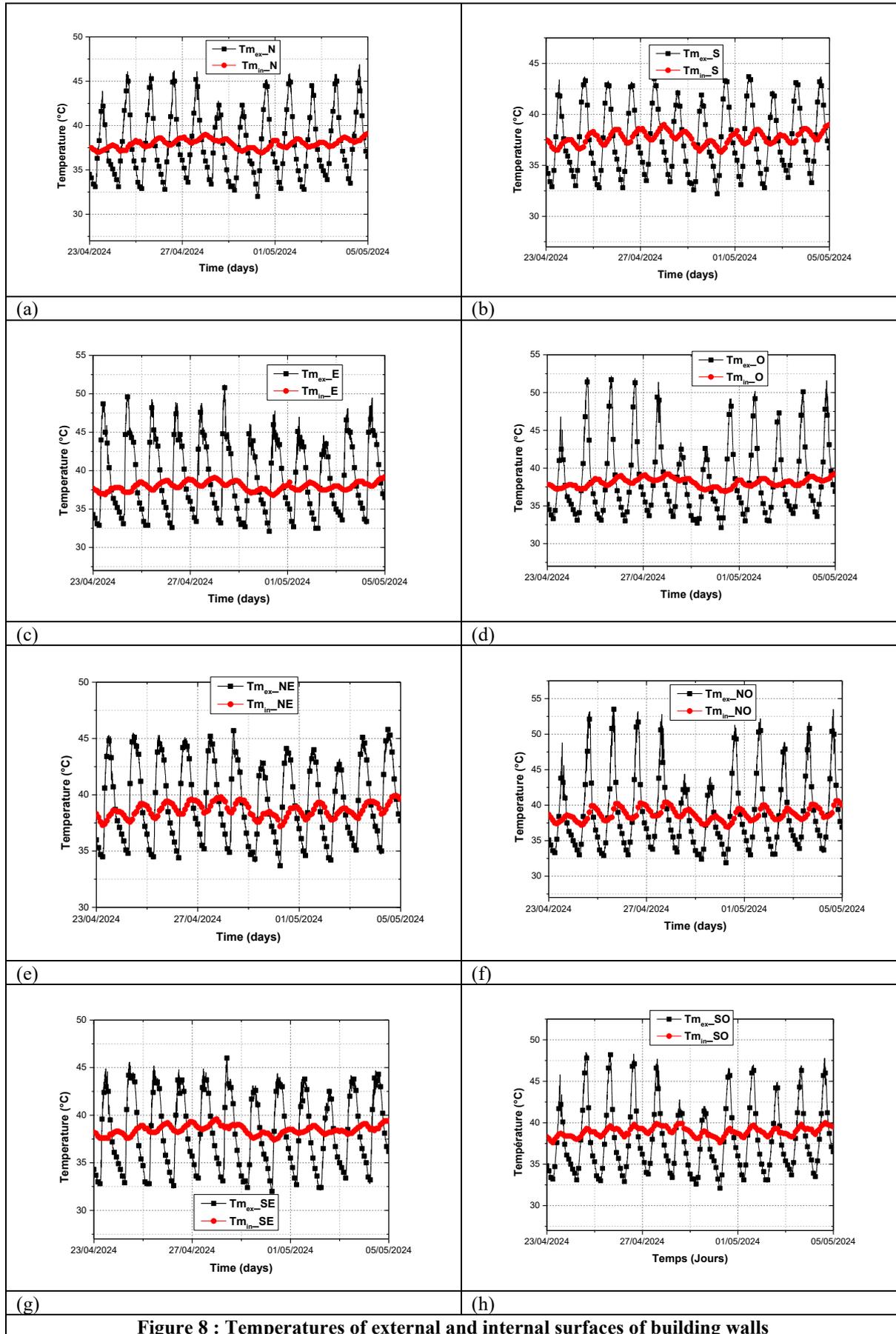
Figure 8 : Temperatures of external and internal surfaces of building walls

Table 4 shows the maximum average external and internal surface temperatures, average damping, average thermal phase shifts and average damping factors for the building's various walls.

Table 4 : Maximum average temperature, medium damping and mean thermal phase shift

	Max. (°C)		Amortization (°C)	Thermal phase shift (h)	Damping factor (%)
	External	**Internal**			
North wall	44,91	38,25	6,8	6 h 49 min	6,20
South wall	43,02	38,52	4,85	7 h 31 min	14,9
East wall	48,9	38,54	10,33	12 h 20 min	6,58
West wall	48,58	38,55	10,02	8 h	5,2
NE wall	45,01	39,25	5,7	6 h 8 min	14,53
NW wall	49,87	39,68	10,19	3 h 4 min	11,39
SE wall	44,9	39	5,89	11 h	8,37
SW wall	46,13	39,56	6,57	1 h 18 min	10,42
Average	46,41	38,92	7,54	7 h 1 min	9,7

Analysis of Table 4 shows that :
✓ The highest temperature peaks were recorded on the northwest, east and west walls, with mean maximum temperatures of 49.87°C, 48.9°C and 48.58°C respectively. At this time of year, the walls receiving the most solar radiation are the east and west walls, but the wall receiving the most heat is the northwest wall. Indeed, during the measurement period (04/23/2024 to 05/05/2024), the north-west wall was exposed, in addition to solar radiation, to radiation received from one of the walls of a cold room installed for testing purposes. This radiation would have contributed to increasing the peak temperature on the surface of the north-west wall.

✓ The greatest temperature differences between the external and internal faces of the walls are found on the east, west and north-west walls, with differences in excess of 10°C (>10°C). Indeed, given their orientation, these walls receive higher solar flux than the other walls, contributing to higher temperature peaks on their external faces. The reductions in peak temperatures on the external faces of these walls are therefore greater than those of the other walls.

✓ The average thermal phase shift is high on east and south-east walls (>11 h), as these walls are oriented to receive peak solar radiation in the morning (before noon), and during this period of the day

the solar radiation received on the building envelope is not excessive. The heat received on these external surfaces therefore takes longer to reach the internal surfaces of these walls. The average thermal phase shift (=6 h 8 min) of the north-east wall is lower than that of the east and south-east walls, because a glass window is located on this wall. Although the pane is protected by a wall overhang, it is heated by convection with air from the outside environment, and this heat contributes to raising the temperature of the inside face of the north-east wall. The peak temperature is reached sooner than expected. The average thermal phase shift values (<8 h) of the other walls (South, North, West) are lower than those of the East and South-East walls, as solar radiation is received on these faces in the afternoon, when all walls are sufficiently heated. Heat is then rapidly transmitted through the walls to their inner surfaces. This reduces the diffusion time of heat peaks to the inner surfaces of these walls. The north-west wall has an average thermal phase shift (=3 h 4 min), a lower value than that expected for the same reasons as the south-east wall. As a result, the pane of glass receives heat by radiation from the face of the cold room opposite the north-west wall. The thermal phase shift of the south-west wall is 1 h 18 min. This value is the lowest because this wall is

strongly influenced by convection between its inner face and the air in the living environment.

✓ The average damping factors for the North, East, West and South-East walls are 6.20%, 6.58%, 5.2% and 8.37% respectively. These values (<8.5%) are the lowest obtained and show that these walls are the most efficient in the building.

✓ The average damping, average thermal phase shift and average damping factor of the building's walls are 7.54°C, 7 h 1 min and 9.7% respectively. The average thermal damping factor for all walls remains below 10%. These values testify to the ability of the building's walls to considerably reduce temperature peaks on external surfaces. At the same time, the building's walls help to stabilize internal surface temperatures. As noted in previous analyses, this performance is due to the thermophysical properties of the bricks used to construct the bioclimatic building walls. These properties give the building's walls excellent thermal inertia, making it a high-performance building when it comes to reducing external temperature peaks. It can therefore make a major contribution to improving thermal comfort.

IV. CONCLUSION

In this article, we set out to study the thermal behavior of the walls and dome roof of a bioclimatic building. To this end, we carried out a measurement campaign during which the temperatures of the external and internal surfaces of the walls and the temperatures of a few points on the external and internal surfaces of the dome were measured. Analysis of the temporal evolution of the temperatures of the outer and inner surfaces of the walls and the domed roof showed that the temperatures of the inner surfaces were more stable than those of the outer surfaces. Evaluation of the average damping of the temperature peaks of the points on the outer surface of the dome, the average thermal

phase shift and the average damping factor of the domed roof built of earth gives respective values of 14.45°C; 6 h 23 min and 12.15%. These values are better than those of corrugated or galvanized roofs. The domed roof helps to reduce heat transmission to the interior. This performance is due to the dome roof shape, the thickness of the dome and the thermophysical properties of the adobe used to build the dome, which gives the roof good thermal inertia.

The evaluation of the average damping of the peak temperatures of the external surfaces, the average thermal phase shift and the average damping factor of the building walls gives respective values of 7.54°C; 7 h 01 min and 9.7%. These values demonstrate the ability of the building walls to considerably reduce the peak temperatures of the external surfaces and to stabilize the temperatures of the internal surfaces. This performance is due to the thermophysical properties of the adobe bricks used for the construction of the walls of the bioclimatic building. These properties give the building walls very good thermal inertia and make the building a high-performance building with regard to the reduction of peaks in external temperatures. It can therefore be of great contribution to improving thermal comfort.

Furthermore, the study reveals that some internal surfaces, including the internal surfaces of the Northwest and Southwest walls (with respective average thermal phase shifts of 1 h 18 min and 3 h 4 min) and the internal surface of the domed roof are influenced by convective heat exchanges. To better appreciate how the internal and external surfaces of the building walls and the domed roof are influenced by convective exchanges, we plan to study the air flow in the bioclimatic building through a numerical study.

Conflict of Interest: No conflicts of interest declared.

REFERENCES

1. Rapport sur l'état mondial des bâtiments et de la construction en 2022, Vers un Secteur des bâtiments et de la construction à émission zéro, efficace et résiliant, Nairobi, 2022.
2. A Bassoud, H. Khelafi, A Mokhtari, A Bada. Bâtiments construits en adobe salin, durabilité centenaire et confort thermique dans un climat désertique. NOMAD 2022 - 4ᵉ conférence internationale francophone Nouveaux Matériaux et Durabilité, IMT Mines Alès; LMGC; LIFAM, Nov 2022, Montpellier, France.
3. Kaboré A., Zoma V., Palm K., Bathiebo D. Joseph, Two dimensional modeling of heat transfers in a ventilated test cell built with various locals materials, 25 (2021), 2348-0130
4. K. TOUSSAKOE, E. OUEDRAOGO, K. B. IMBGA, A. MESSAN, F. P. KIENO, Caractérisation mécanique et thermo-physique de l'adobe utilisé dans la voûte nubienne, Afrique SCIENCE, 19(5) (2021) 186-199
5. Césair. M. Hema, Geoffrey Van Moeseke, Arnaud Evrad, Luc Courard, A. Messan, Vernacular housing practices in Burkina Faso: representative models of construction in Ouagadougou and walls hygrothermal efficiency, ScienceDirect (Energy Procedia) 122 (2017) 535–540
6. Sandwidi Sayouba, Recherche de nouveaux matériaux de construction à faible intensité énergétique, Thèse, Université Jospeh KI-ZERBO, 2022
7. Kaboré, B. Ouédraogo, S. Sandwidi, V. Zoma, H. Kaboré, K. Palm, Experimental Study of the Thermal Behavior of a Bioclimatic Building Prototype in a Sahelian Zone, Smart Grid and Renewable Energy, 15 (2024) 187-199. https://doi.org/10.4236/sgre.2024.158011
8. Ousmane COULIBALY, Contribution à l'élaboration d'une réglementation thermique et énergétique des bâtiments au Burkina Faso : Données de base multiparamétriques et modélisation thermo-aéraulique sous CoDyBa et TRNSYS, Thèse, Université de Ouagadougou, Burkina Faso, 2011.
9. G. D. Morris, Bulding Heat transfert, John Wiley and Sons Ltd, 2004.
10. O. Emmanuel, C. Ousmane , O. Abdoulaye et M. Adamah , Caractérisation mécanique et thermophysique des blocs de terre comprimée stabilisée au papier (cellulose) et/ou au ciment, Journal of materials and engineering structures, 2 (2015) 68–76.
11. M. Fabio, Etude de l'influence de l'inertie thermique sur les performances des bâtiments., Paris : Ecole Nationale Supérieure des Mines de Paris, Thèse de Doctorat, 2014.

******