STUDY OF THE THERMAL BEHAVIOUR OF AN EXPERIMENTAL BUILDING AT THE NATIONAL RESEARCH CENTRE FOR DEVELOPMENT IN CHAD

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Abstract

This experimental study of thermal behaviour is being carried out as part of the search for solutions to exploit local building materials. It focuses on an experimental analysis of a 24 m^2 office-type cell built in N'Djamena. Measurements of the temperature and humidity of the indoor and outdoor air and of the walls of the envelope were taken using hygrothermal sensors of the SHT75 and SHT35 types. Temporal variations in temperature were determined on the internal and external faces of the walls, as well as in the walls making up the envelope of this cell. The results obtained were used to analyse and understand the operation of the experimental cell envelope and its thermal behaviour. The thermal input through the roof is greater, as the temperature at sheet level reaches 56.80°C at the same time as the outside temperature reaches 41.70°C. An overheating effect occurs in the attic ceiling. This analysis showed that the experimental cell did not meet the required thermal comfort conditions of a maximum temperature of 29°C according to the literature. These results have made it possible to understand and analyse the thermal behaviour of the cell.

Key words: Thermal behaviour, local materials, thermal comfort and insulation in warm climates

1. Introduction

This work, carried out as part of the CABET (Construction Alternative Basse Energie au Tchad) research and development project, relates to the effort to master building thermal engineering with a view to energy efficiency and to making the most of local building materials in the construction sector, which is a worldwide concern. This concern has led to the adoption of thermal and energy regulations (ISO-13790, 2008) and (ASHRAE, 2002). To this end, an experimental cell builted and instrumented with thermo-hygrometric sensors in order to quantify the overall indoor environment and in particular the thermal ambience, which is characterised by two physical quantities: the temperature and relative humidity of the air and the walls making up its envelope. However, the so-called contemporary detached houses built in Chad, particularly in the city of N'Djamena, do not meet the requirements of comfort in general and thermal comfort in particular. This is due to the fact that a number of criteria are not taken into account from the outset of the design phase, such as architectural construction, thermal insulation of the external envelope of houses, thermal inertia and, above all, ignorance of the thermo-physical properties of building materials.

Analysis of the thermal behaviour of a building in real climatic conditions gives an idea of the real situation of the interior environment and hence of 'thermal comfort', taking into account the physical and thermal characteristics of the materials making up its envelope and their arrangement (BATAN, 2011).

The parameters often measured are the temperature and relative humidity in the different thermal zones defined inside the building. These two parameters are very important criteria in defining and determining the thermal comfort conditions for occupants (ASHRAE, 2002) and (ISO 7730, 1994).A number of numerical and experimental research studies have focused on thermal behaviour in buildings (Derradji, et al., 2011), (Chelghoum, 2011) and (BATAN, 2011). Some have studied the influence of geometric parameters, others the influence of thermo-physical parameters, as well as the nature of materials (Fati, 2021) and climatological parameters (Oudrane, Aour, Zeghmati, Chesneau, & Hmouda, 2018) on the thermal behaviour of buildings.

The aim of this study is to analyse the thermal behaviour of the experimental cell under real climatic conditions. The analysis of the thermal behaviour of the cell involved an in situ study and a campaign of in-depth measurements of the cell.

2. Materials and methods

2.1. Thermo-physical properties of materials

The various values of the thermo-physical properties of the materials used in the construction of the experimental cell are given in Table 1. These materials include : cement-stabilised mud bricks (CSB), aluminium sheet, plywood, mortar plaster, tiles and glass.

Table 1: Thermo-physical properties of materials

Materials	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Density (kg,m^{-3})	Heat Capacity (J,kg^{-1},K^{-1})
CSB	0.586	1487	1115
Aluminium sheet	160	2800	880
Plywood	0.14	600	2720
Mortar plaster	1.15	1800 - 2100	880
Tiles	1.15	1800	700
Glass	1.2	2530	720

2.2. CABET experimental cell

The CABET (Construction Alternation Basse Energie au Tchad) experimental cell that is the subject of this study has a living area of approximately 24 m^2 and is therefore similar to a conventional office or single room commonly found in Chad (Figure 1). It was built using the materials listed in Table 1 on the CNRD site, more specifically in the town of N'Djamena. The town of N'Djamena is part of the BSh climatic zone, known as the dry, hot steppe climate according to the Köppen climate classification. This climatic zone is characterised by a hot, dry summer.

Figure 1: CABET experimental cell, seen from the north and west

Representing a full-size building but of small dimensions, it consists of vertical opaque walls, two single-glazed windows, a glazed door and a roof incorporating a ceiling.

2.3. Description of the cell's instrumentation

Temperature and relative humidity measurements at various points in the cell carried out using SENSIRON SHT75 and SHT35 type thermo-hygrometers (Figure 2). In all, nineteen sensors installed and connected to two acquisition and recording units (SHT DaqBox) through the envelope and inside the cell. These sensors are regularly calibrated to check the results of each sensor and detect any anomalies in the measurements.

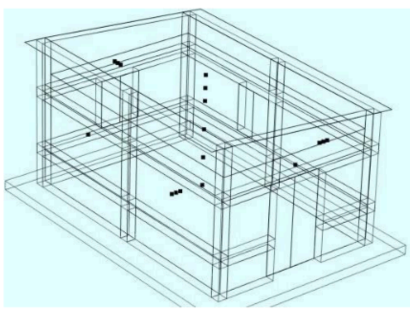

Figure 2: Position of the various sensors in the CABET experimental cell

A DAVIS Vintage Pro 2 mimi wireless weather station is installed near the cell on a wall approximately 5 metres above the ground. This weather station is used to acquire and record the various parameters of the site's climatic conditions, namely: air temperature, relative air humidity, atmospheric pressure, wind speed and direction, as well as direct horizontal solar radiation and precipitation.

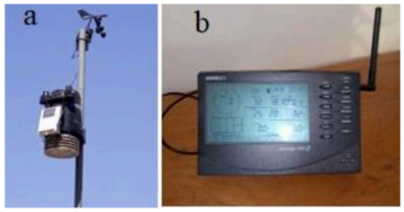

Figure 3: Weather station (a) and its acquisition and recording console (b)

3. Results and discussion

This study analyses the results of the thermo-hygrometric measurements carried out during the most unfavourable period of the summer, i.e. the month of April, on the thermal behaviour of the CABET experimental cell. These results relate to the days of 09 and 10 April 2022.
In order to carry out this study of thermal behaviour, we chose the results of the measurements when the cell was in free evolution, i.e. there were no occupants (no activities), and the door and windows remained closed all the time during the measurement periods. There were also no other internal heat inputs. The results of the measurements are as follows:

3.1. Evolution of ambient temperatures (outside and inside)

In order to take account of the vertical difference in temperatures in the cell, sensors were installed vertically at three positions. Figure 4 shows the changes in outdoor and indoor air temperatures at the different sensor positions. These temperatures move in the same direction. Despite the high thermal inertia of the vertical walls, the measurements show a temperature damping of around 8°C. The average air temperature inside the cell is between 34°C and 41°C most of the time, which does not meet the requirements for thermal comfort during the summer in a hot climate (ANSI/ASHRAE-55-2017, 2020) and (NF EN ISO 7730, 2006) with a maximum temperature of 29°C (IFDD, 2015). This can be explained by the lack of thermal insulation of the walls and especially the roof.

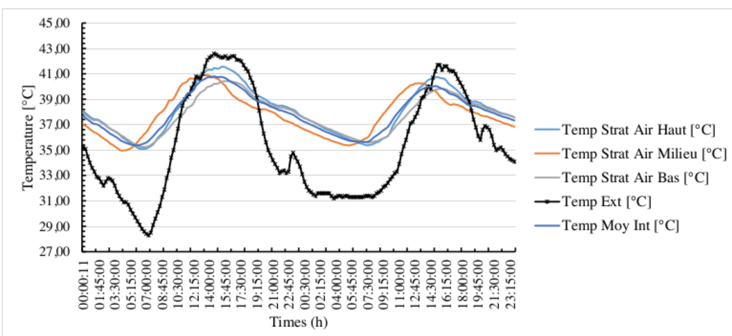

Figure 4: External and internal temperature trends

3.2. Evolution of the temperatures of the internal surfaces of the walls and ceiling

The variation in the temperatures of the internal surfaces of the walls and ceiling is shown in Figure 5. It can be seen that the temperatures of the internal surfaces of the walls and ceiling show asymmetries of variation with them, known as radiant temperatures. These asymmetries in radiant temperatures can be a source of thermal discomfort in the cell (ANSI/ASHRAE-55-2017, 2020). It should be noted that the temperature of the inside face of the ceiling has a higher thermal amplitude, with a maximum of 45.59°C, than the temperature of the outside air, with a maximum of 42.6°C. This can be explained by the fact that the attic of the ceiling acts like a thermal oven due to the lack of thermal insulation in the roof.

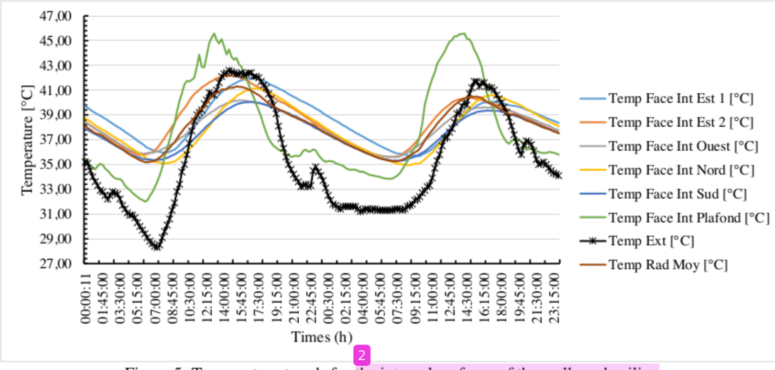

Figure 5: Temperature trends for the internal surfaces of the walls and ceiling

Two sensors were installed on the inside of the east wall to check the thermal homogeneity of the surface. The results of the measurements showed that there is a difference in temperature, with a maximum difference of 2.7°C (Figure 6). This result shows that the internal surface of the east wall of the cell is not isothermal. The same would be true for the other wall surfaces.

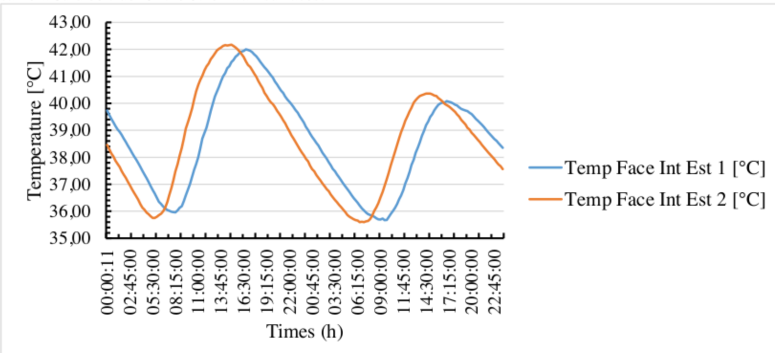

Figure 6: Temperature trends on the inside surface of the east wall

3.3. Temperature trends on the external surfaces of the walls

Figure 7 shows the temperature trends on the external surfaces of the cell walls. These temperatures evolve differently according to the path of the sun. The figure shows that the temperature of the external face of the east wall reaches its maximum value before those of the south and west external faces respectively.

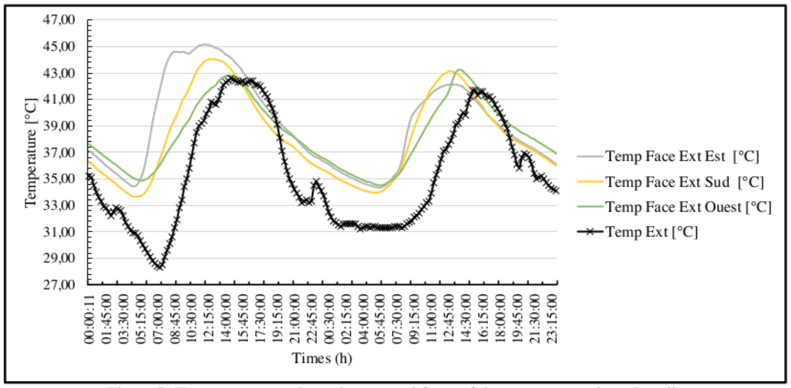

Figure 7: Temperature trends on the external faces of the east, west and south walls

3.4. Temperature trends through the vertical walls

In addition to the sensors installed on the inside faces of the vertical walls (walls), sensors are installed on the outside faces and in the walls to a depth of about 2/3 of the wall thickness. In this section, we analyse the temperature distribution across the cell walls. Figure 8, Figure 9 and Figure 10 show that the temperatures of the internal faces, the walls and the external faces have similar variations and move in the same direction. The temperatures of the external faces reach maxima of 44.06°C, 45.15°C and 43.25°C, while those of the internal faces reach 40.05°C, 42°C and 40.17°C respectively for the South, East and West walls.

We have observed temperature damping between the external and internal faces of the walls. These are approximately 4°C, 3.16°C and 3.08°C with phase shifts of 3h15, 5h and 1h15 respectively for the South, East and West walls.

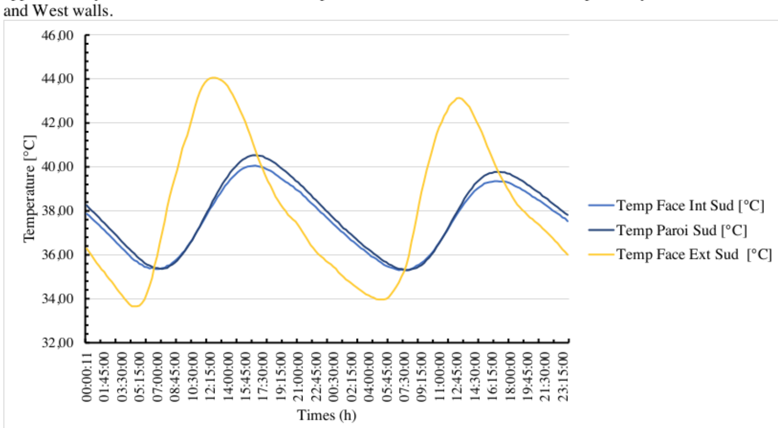

Figure 8: Temperature trends through the south wall

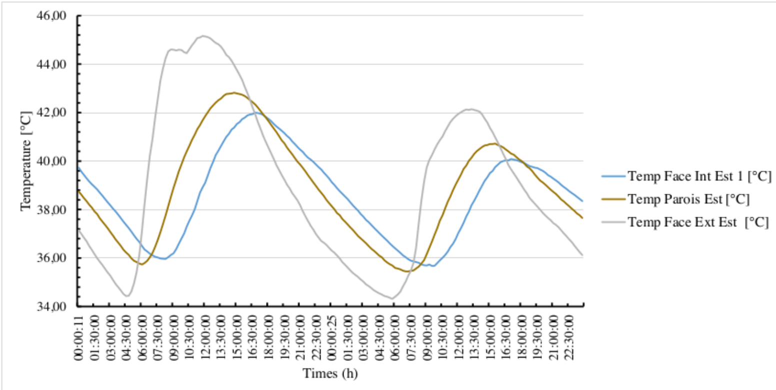

Figure 9: Temperature trends across the east wall

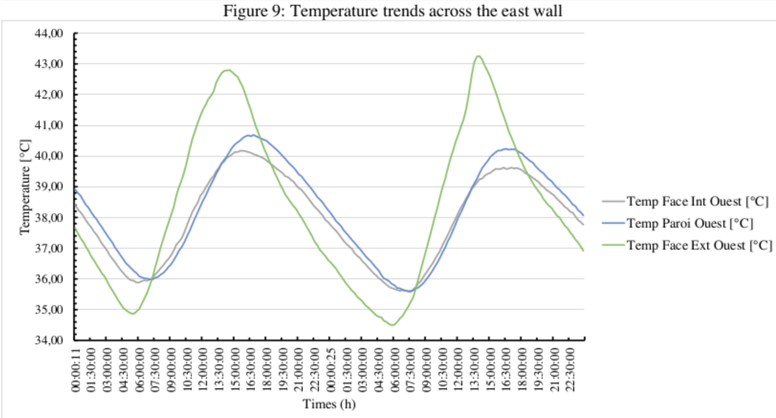

Figure 10: Temperature trends through the west wall

3.5. Temperature trends through the roof

In order to study heat transfer through the roof, three hygro-thermal sensors were installed on the inside of the ceiling, in the roof space and on the inside of the metal sheet. Figure 11 shows the temperature trend across the roof of the cell. At sheet metal level, the temperature measurement carried out gave a maximum of 56.80°C on 10 April 2022 at 11:45 a.m. and a maximum temperature of 45.59°C on the inside of the ceiling. This gives a difference of around 11.21°C. On the same day, the outside temperature reached a maximum of 41.70°C. This increase in temperature at roof level is due to the accumulation of heat in the roof space. The attic therefore acts as a thermal oven, which shows that the thermal gains through the roof are greater than those through the walls. We can therefore see that solar loads are much greater at roof level than for the cell envelope as a whole.

The work carried out by Derradji et al. has shown that good thermal insulation can reduce the heat flow towards the interior of the home (Derradji, et al., 2011). The lack of thermal insulation leads to very significant overheating in the cell.

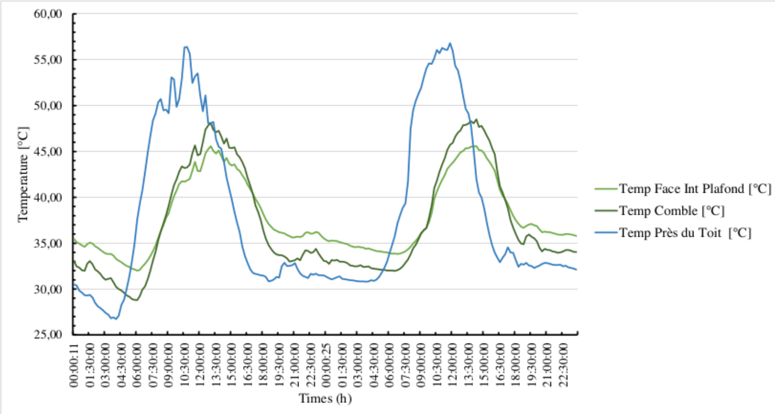

Figure 11: Temperature changes through the roof

3.6. Vertical distribution (stratification) of indoor temperatures

A large vertical difference (stratification) in air temperature between the floor and the ceiling can cause thermal discomfort in a building (NF EN ISO 7730, 2006) and (ANSI/ASHRAE-55-2017, 2020).

Figure 12 shows the vertical profile of the maximum temperature for the three thermo-hygrometric sensors placed vertically and from the ceiling. The vertical temperature difference obtained is approximately 6.14°C for a measurement interval of 1.5 m between the low sensor and the ceiling. This temperature gradient of 6.14°C is very significant because of the solar gain absorbed by the roof, the heat exchange gain and the thermal accumulation effect (overheating) in the attic. The ANSI/ASHRAE 55 standard gives maximum values of 3°C and 4°C for seated and standing persons respectively (ANSI/ASHRAE-55-2017, 2020). Given the significant vertical temperature difference, the experimental cell does not meet thermal comfort conditions.

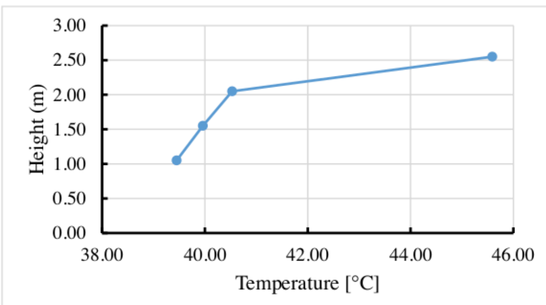

Figure 12: Vertical profile of stratified temperature as a function of height

Figure 13 shows the evolution of indoor air temperatures as a function of time for vertically positioned sensors. The temperatures measured by the three sensors placed vertically vary between 35.35°C at night and 40.75°C during the day. Even the temperatures measured at night are higher than those required by Givoni's bioclimatic diagram adapted to climates (IFDD, 2015).

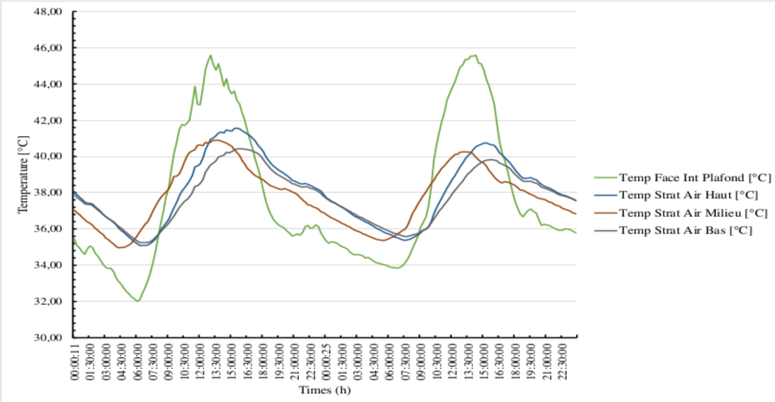

Figure 13: Evolution of the vertical difference in indoor air temperatures

3.7. Change in relative humidity

Figure 14 shows the change in relative humidity inside and outside the cell. The relative humidity outside the cell generally varies between 52% at night and 10% during the day. On the other hand, the relative humidity inside the cell varies less during the day (16.46%) than at night (21.85%). What's more, this relative humidity evolves in the same way in the three measurement sensor locations in the cell. These low values of relative humidity inside the cell can be explained by the fact that the cell is in free evolution. This implies a lack of aeration due to the absence of ventilation or air infiltration into the cell.

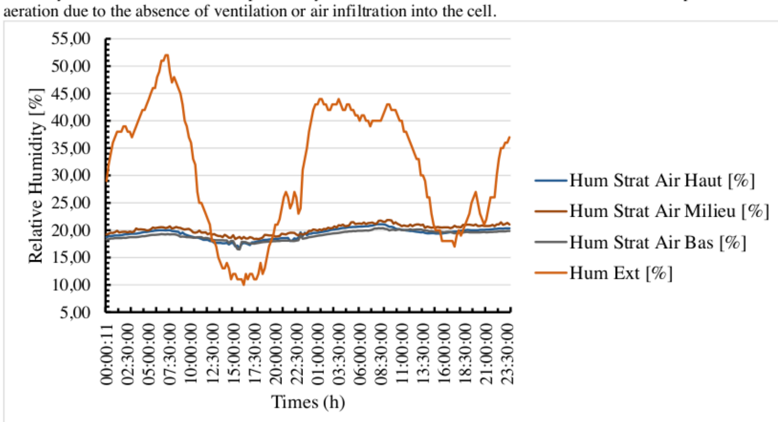

Figure 14: Change in relative humidity

Conclusion

The aim of this work was to analyse the thermal behaviour of the CABET experimental cell under climatic conditions. The experimental results presented have made it possible to analyse and understand the operation of the envelope of the experimental cell and its thermal behaviour. The results show that the temperatures measured are similar. The thermal input through the roof is greater, as the temperature at sheet level reaches 56.80°C at the same time as the outside temperature reaches a maximum of 41.70°C. On the one hand, an overheating effect is taking place in the ceiling space. On the other hand, this analysis showed that the experimental cell does not meet the thermal comfort conditions required by Givoni's bioclimatic diagram (IFDD, 2015) and the ANSI/ASHRAE (ANSI/ASHRAE-55-2017, 2020) and ISO 7730 (NF EN ISO 7730, 2006) standards on the vertical temperature difference and radiant temperature asymmetry of its envelope.

Bioclimatic design and the use of passive techniques are solutions to be explored, especially for a country like Chad. A look at vernacular construction, which used unchanging techniques closely linked to the climate, has highlighted the inconsistency in the construction of so-called contemporary housing. The result is a habitat that is poorly adapted to its climatic context. This is particularly true in regions with hot, dry climates, offering great potential for bioclimatic design and sustainable construction, particularly in terms of energy efficiency. The solution lies in understanding the thermal behaviour of the building envelope, and even in the use of appropriate passive cooling solutions.

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