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Simulation Study of Thermal Comfort in Residential Building Types: The Case of Lokoja, Nigeria

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ABSTRACT: *Thermal comfort is an important factor for the design of buildings that offers comfortable indoor environment for the wellbeing of building occupants. There are several residential building typologies at different locations in the world. These includes bungalows, duplexes and block of flats. Despite previous studies on thermal comfort in Nigeria, there is a lack of research data on the performance of different building types, especially in terms of thermal comfort. Hence, this study evolved to investigate three popular types of residential buildings in Nigeria. The research outcome aims to provide data for theoretical evolution on the thermal behavior of these building types. The paper used dynamic thermal simulation, natural ventilation mode to analyze three residential buildings in Lokoja, Nigeria using hourly weather data for a period of 10 years. The simulation results showed that the annual operative temperature for the three cases were 33.36^{0}C, 33.62^{0}C and 33.65^{0}C. This revealed that there is no significant difference between the operative temperatures of the three case studies. However, there were marked differences between both the monthly and annual solar gains of the case buildings. The total annual gains for the three case studies were 24118.27kWh, 20497.90kWh, and 39493.09kWh. Although there was no significant difference in the performances of the case buildings, there performed differently in terms of both operative temperature and solar gains. The simulation results confirmed thermal discomfort in residential buildings in the study area. This calls for improvement in the design of residential buildings in the study area to enhance thermal comfort and reduce energy demand due to overdependence on mechanical cooling systems. This study has provided data that is expected to guide design professionals and other stakeholders in the building industry in their decisions regarding the thermal performance of residential building types in the study area and in similar climates.*

KEYWORDS: Thermal comfort, operative temperature, solar gains, simulation, building types.

INTRODUCTION

ASHRAE Standard 55 (2010) defined thermal comfort as the condition of the mind in which satisfaction is expressed with the thermal environment. Hensen (1991) referred to thermal comfort as a state where no driving impulse exist to modify the environment through behaviour. Comfort is a human feeling of complete mental and psychological wellbeing with the built environment (Givoni, 1976).

Thermal comfort is among the most important requirements for the design of buildings (Nicol, Humphreys and Roaf 2012) maintained that thermal comfort is among the most relevant aspects of users' satisfaction and energy requirements of buildings. Thermal discomfort can greatly influence energy demand of buildings but can be managed through energy efficiency measures. Moore, Schüwer, Thomas, & Lindström (2013) identified two strategic approaches that have been developed regarding the four major climatic zones of the world. These strategies are the "Easy Efficiency Strategy" and the "Advanced Efficiency Strategy". To embark on energy saving measures in any climatic location, it is important to study the thermal performance of existing buildings. Hence, a thorough understanding of the level of thermal comfort and energy requirements of different building typologies are key to improving thermal comfort and energy efficiency in buildings. This is important as buildings accounts for nearly 40% of the total energy use worldwide and are accountable for one-third of global greenhouse gas (GHG) emissions (Pearce and Ahn, 2013).

There seems to be a lack of research data on the thermal performance of different building types in different climates. The researcher is of the view that relevant data on the thermal performance of different residential building types will guide stakeholders in trying to identify measures to downsize energy consumption. Hence, this study evolved to provide data that would guide stakeholders in the building industry towards improving thermal comfort and energy efficiency in residential building types.

Thermal comfort models

The definition of thermal comfort as a state of mind base on a state of condition makes it difficult to assess human comfort conditions. However, there are some indicators of thermal comfort. The most important indicator is air temperature. This may be because majority of people found it easier to use and refer to. Nevertheless, for a broad understanding of thermal comfort, understanding of other related variables are necessary. These involve both personal and environmental variables.

Macpherson (1962) outlined six factors that can have significant influence on thermal sensation. Four of these variables are environmental (physical) while the other two are personal. The environmental factors are air temperature, relative humidity, air velocity and radiant temperature while the personal variables are clothing insulation and activity level (metabolic rate). Fanger, (1970) developed a comfort equation assessing thermal comfort using the six comfort variables based on human heat balance in a controlled climate chamber under steady-state conditions. This led to the development of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) as comfort indices, which are used in both ASHRAE Standard 55 and ISO EN 7710 to determine thermal comfort standards for air-conditioned buildings in USA and Europe respectively. Many other countries in the world have adopted PMV and PPD to define thermal comfort conditions in air-conditioned buildings (Chandel and Sarkar, 2015).

Predicted mean vote (PMV)

Predicted Mean Vote (PMV) is used to describe a thermal scale that ranges from Cold (-3) to Hot (+3). On the thermal scale, ASHRAE recommended between -0.5 to +0.5 as acceptable PMV range for thermal comfort in air-conditioned buildings. Predicted Percentage of Dissatisfaction (PPD) is the term used to predict the percentage of building occupants that are likely to be dissatisfied with thermal conditions. PPD depends on PMV so that as PMV proceeds from neutral (0), PPD increases. ASHRAE Standard 55 recommended less than 10% persons dissatisfied as acceptable PPD range for thermal comfort in interior spaces.

ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy was released in 1966. Although it was originally developed to provide guidelines for buildings with centrally controlled HVAC, it has been adopted generally across all climates, populations and building types to determine thermal comfort conditions (Brager and de Dear, 2000).

A study by Kempton and Lutzenhiser (1992) claimed that reliance on ASHRAE Standard 55 has allowed the omission of relevant contextual, cultural and social variables in the prediction of thermal comfort leading to too much emphasis on the need for air conditioning in buildings. This argument led to the development of an alternative comfort standard based on field measurements. It centred on contextual and perceptual variables which were absent in laboratory experiment that led to ASHRAE Standard 55. Toward this end, further research emerged focusing on three primary modes of adaptation: physiological, behavioural and psychological (Brager and de Dear, 2000). Empirical research on this subject led to the development of adaptive thermal comfort standard as relevant alternative to PMV for prediction of thermal comfort in naturally ventilated buildings.

Adaptive thermal comfort

Adaptive thermal comfort relays satisfactory indoor temperature ranges to the monthly mean outdoor temperature. Adaptive comfort theory is based on the connexion between building occupants and the outdoor environment. This link and the control over their immediate environment make the building occupants to adapt to wider range of thermal comfort conditions (Nicol and Humphreys, 2002; Brager and de Dear, 2001). It operates on the supposition that when people experience thermal discomfort, they react to reinstate thermal comfort. Adaptive thermal comfort model "is the most suitable for free-running naturally ventilated buildings where mechanical cooling and heating are not present and occupants have total control on operable windows" (Chandel and Sarkar, 2015, p.876).

This study adopted the adaptive thermal comfort model to predict thermal comfort temperature for Lokoja, Nigeria. GIZ (2015) revealed based on ASHRAE Standard 55 that for Nigeria with a monthly mean outdoor temperature of nearly 26^0C, 90% of the population will be comfortable at temperatures up to 28^0C. This assumption was used for the simulation of the case studies.

Case study

There are several building typologies in Lokoja, the study area. These include duplexes and bungalows in detached, semi-detached and block of flats. The adoption of multiple case study became necessary to understand the similarities and differences if any between the most popular buildings types particularly regarding thermal comfort. The case studies for this research have been chosen to provide relevant information, especially regarding thermal performance of existing residential building types in the study context. The case studies were purposefully selected due to the need to generalize its analytical findings to similar building typologies in the study area (Johansson, 2003). The findings from the analysis of case studies is expected to guide building development towards achieving thermal comfort and energy efficiency in residential buildings. The researcher is of the view that the study of these cases could provide relevant data for theoretical evolution on this subject.

RESEARCH METHODS

Building simulation

This study adopted simulation as the main approach for investigating thermal performances of the selected building types. Building simulation is an important tool for analysing the effects of Energy Conservation Measures (ECMs) and their complex interactions. Kaplan, Caner, & Vincent (1992) posited that it is a more comprehensive, efficient and accurate method of building assessment compared to other tools.

Majority of building simulation programs have two components, a graphical user interface (GUI) and the simulation engine. While the graphical user interfaces (GUIs) determine the ease of use of programs, the simulation engine determine the reliability of the simulation results. Building performance modelling and simulation for this study used DesignBuilder as the GUI and EnergyPlus as the simulation engine.

Robust weather data is relevant to the design of energy efficient buildings. Radhi (2008) maintained that the reliability of the simulation results depends largely on the weather data especially for the calculation of annual thermal performance of buildings. The duration covered by weather data is a relevant factor to consider before obtaining weather file for simulation. EnergyPlus warned against using single year, Test Reference Year-type (TRY) weather data for energy simulation programs as it does not represent typical long-term weather patterns. (EnergyPlus, 2018). Hence, the simulations of the selected cases were conducted using hourly weather data of Lokoja for 10 years purchased from Meteonorm. The single dataset for Lokoja covered temperature and radiation periods from 2000-2009 and 1991-2010, respectively.

The case study buildings

Three residential building types were selected at random to represent the various building typologies in the study area. These are detached, semi-detached and block of flats.

Case study 1

This building is one of the 200 Housing Units located along Ganaja Road, Lokoja, Nigeria. The functional spaces in the building are the entrance porch (also used as carport), living, dining, three bedrooms, kitchen, store and terrace. Figure 1 and 2 show the floor plan (reproduced) and 3D views of some of the housing units captured by the researcher during the process of data collection.

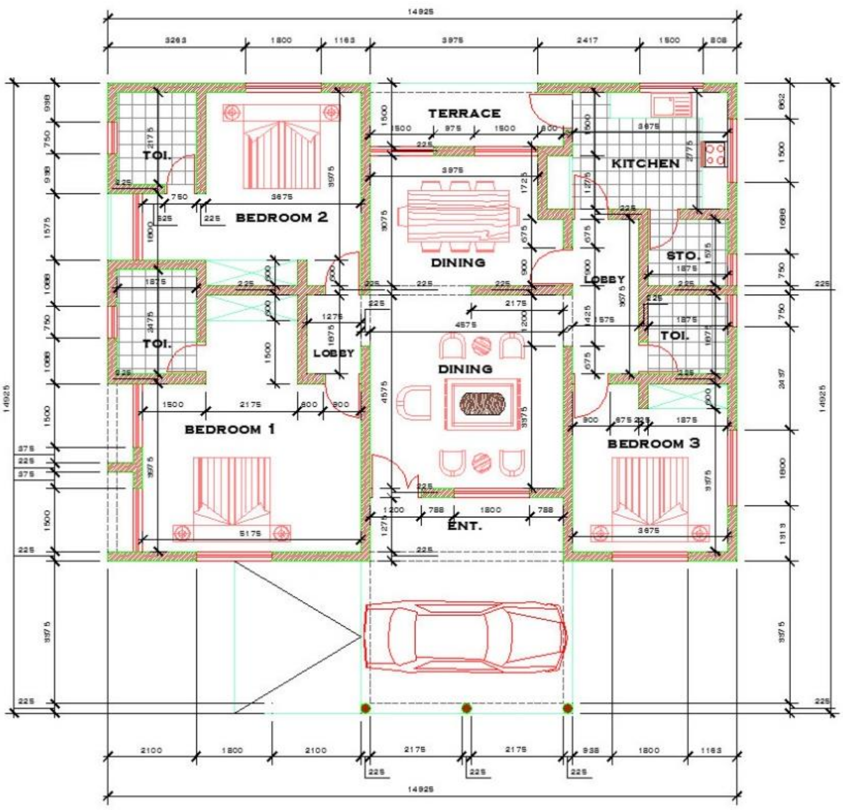

Figure 1. Floor plan showing the layout of functional spaces

Figure 2. 3D view of case study 1 showing other housing units

The external and internal walls of the building were constructed with 9 inches hollow sandcrete block. Both the external and internal walls were plastered using sand/cement plaster. The external walls were painted with white colour emulsion paint.

All windows were single-glazed aluminium sliding windows. The windows were fitted with reinforced concrete overhang and fins of about 300mm as shown in figure 2. The window sills were also fitted with 300mm reinforced concrete projection. The windows were also fixed with aluminium burglar-proof to enhance the security of the building and discourage the activities of burglars and thieves. Mosquito blinds were also fixed on the windows to prevent mosquitoes and other insects from entering the building.

The ceiling was constructed using asbestos ceiling boards, 50 x 50mm hardwood noggins and boarded using battens. The surface of the ceiling was finished with white emulsion paint. The ceiling height from the floor surface was 2.833m. This measurement was taken during the survey of the building. The uninsulated pitched gable roof construction was covered with grey colour corrugated asbestos roofing sheets. The roof has neither roof vent nor eave vent for convection airflow, which can help to cool interior spaces. The approximate size of the eave was 600mm. The 25x250mm hardwood fascia board was finished with brown oil paint.

Case study 2

This building is located beside commissioners' quarters, along Ganaja road, Lokoja, Nigeria. The functional spaces are shown in figure 3. Figure 4 shows a 3-dimesional view of the building.

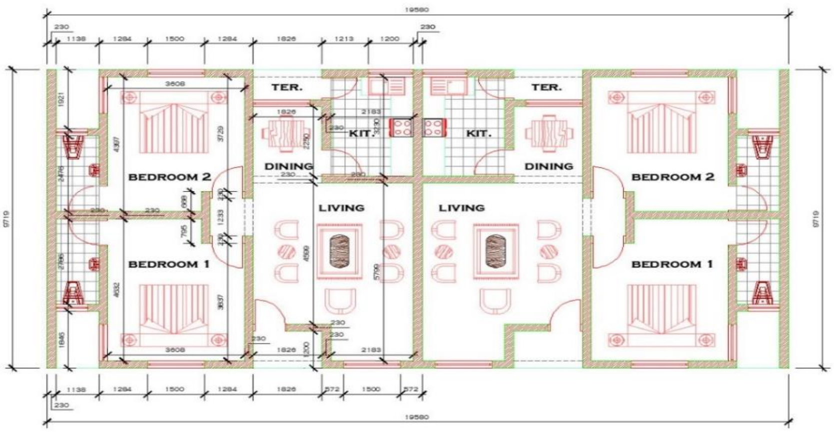

Figure 3. Floor plan of the case study showing the layout of functional spaces

Figure 4. 3D view of case study

The building materials and the construction method for this case study are nearly the same with case study 1. To avoid repetition, the following points highlight areas where there are differences between this case study and case study 1.

- The external walls were painted with cream colour emulsion paint.
- Building do not have shading devices on external windows
- The ceiling height from the floor surface measured during the survey was 2.762m.
- The approximate size of the eave was 500mm.
- The wooden fascia board was painted with black oil paint.

Case study 3

This building is located behind Lokongoma Phase 1 quarters, Lokoja, Nigeria. It was selected for evaluation because it portrays some of the challenges that are typical of bungalow – multifamily or row houses in Lokoja, Nigeria. These challenges include lack of proper ventilation and inadequate daylighting leading to overdependence on mechanical cooling systems and artificial lighting. The functional spaces are shown in figure 5 while figure 6 presents a 3-dimesional view of the building.

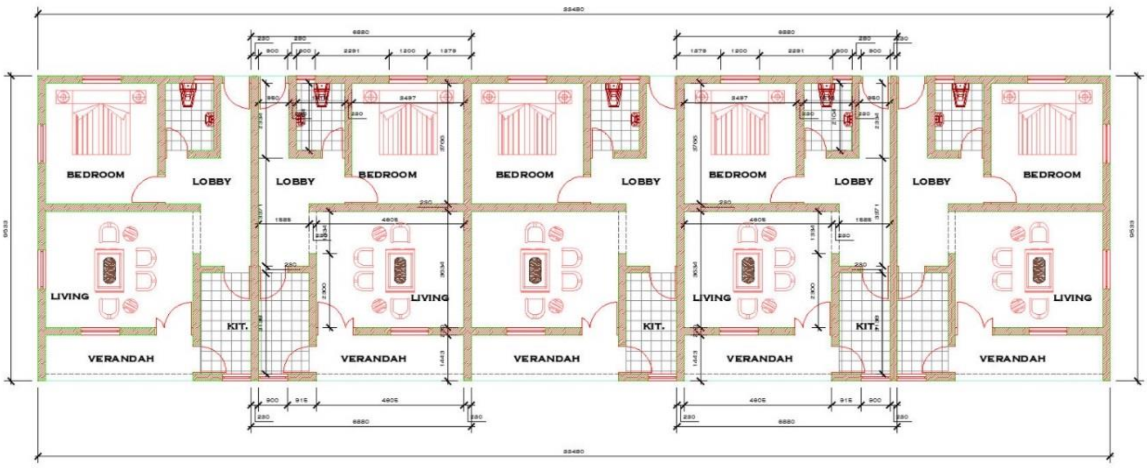

Figure 5. Floor plan of case study 3 showing the layout of functional spaces

Figure 0. 3D view of case study 3

The building materials and the construction method for this case study are virtually the same with case study 2. The areas where there are differences between case study 3 and case study 2 are presented below.

- The external walls were painted with TexCote paint.
- The ceiling height from the floor surface measured during the survey was 2.567m.
- The wooden fascia board was painted with brown oil paint.

Modeling and simulation of case studies

The orientation of case studies 1, 2 and 3 were measured during the site surveys at 147^0 SE, 247^0 SW and 54^0 NE respectively. These orientations were used for the modelling and simulation of the different cases. The construction materials for the case studies were identified during measurements and observation survey. These construction specifications were selected from DesignBuilder template and used for modelling and simulations. For materials that were not directly available for selection, adjustments were made to existing templates to achieve similar properties. Natural ventilation mode was adopted as the HVAC template since the buildings were assumed to be free-running (no heating/cooling). Table 1 shows the construction materials for floors, walls and roof for the three cases.

Building elements	Material	U-Value
Floor	150mm Concrete slab	2.602 W/m^{2}K
Wall	225x450x225mm Hollow lightweight concrete block	1.867 W/m^{2}K
Roof	Uninsulated pitch roof	3.447 W/m^{2}K

Aluminium metal doors of three layers and hardwood solid doors were assumed for external and internal doors respectively. 'Single glazing, clear, no shading' template and single clear 6mm glazing type were assumed for the modelling of windows. All windows were assumed to be opened by about 50 percent (sliding windows).

Air changes per hour (ac/h) of 2.5 was adopted considering the use of insects' net, drapes and burglary proof on windows, which limits airflow. Figure 7, 8 and 9 show 3-dimensional models of the three cases respectively.

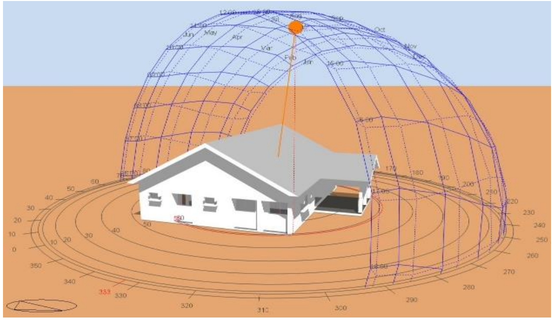

Figure 7. DesignBuilder 3D model of case study 1

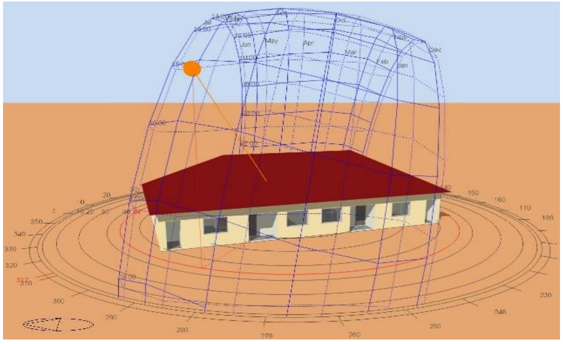

Figure 8. DesignBuilder 3D model of case study 2

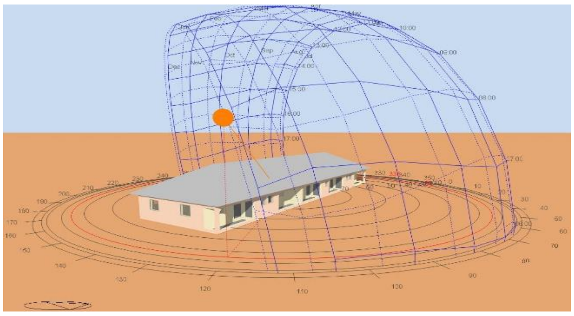

Figure 9. DesignBuilder 3D model of case study 3

RESULTS

Case study 1

The lowest operative temperature was recorded in August at 31.01^{0}C while the highest operative temperature occurred in March at 35.27^{0}C. On the other hand, the highest solar gain occurred in December at 2569.74kWh while the lowest solar gain was recorded in July at 1578.81kWh. This result shows that higher solar gains might not mean higher operative temperature. Other factors may be responsible for this as the highest operative

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temperature occurred in March while the highest solar gains occurred in a different month in December. Figure 10 and 11 show the monthly operative temperature and annual simulation results for case study 1 respectively.

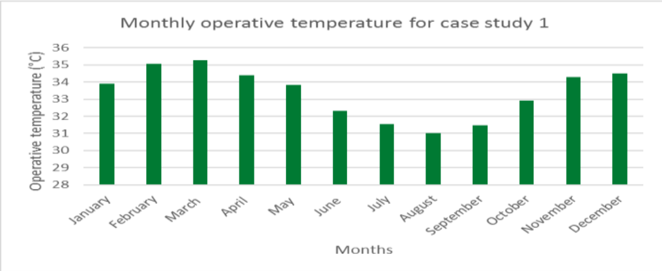

Figure 10. Monthly operative temperature for case study 1

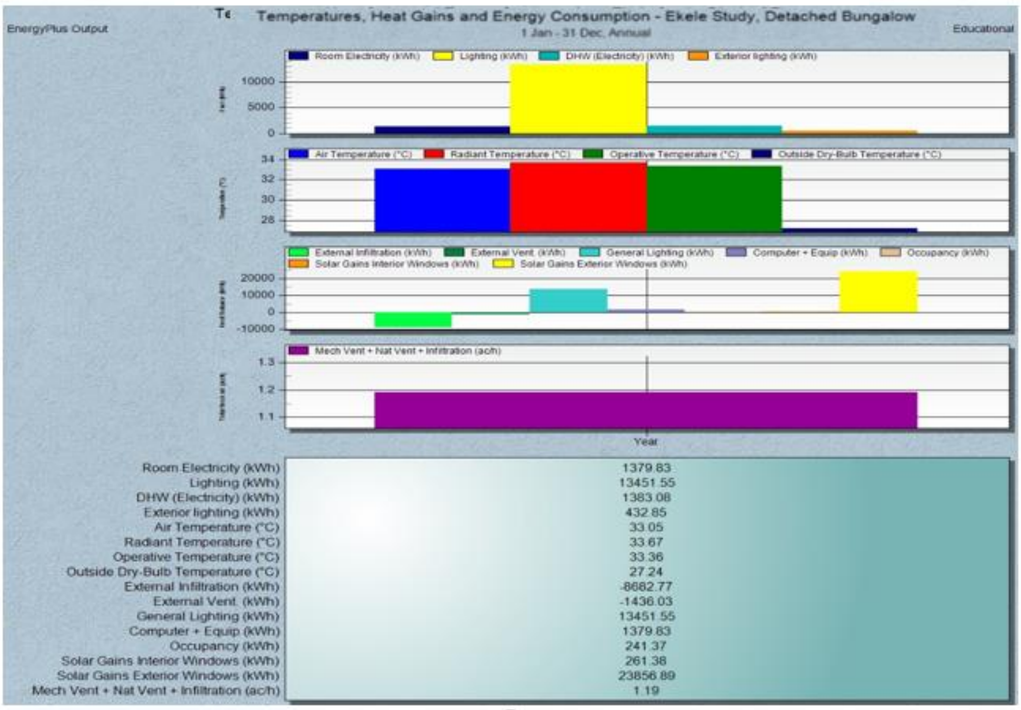

Figure 11. Annual simulation results for case study 1

Case study 2

The lowest operative temperature for this case study occurred in August at 31.52^{0}C while the highest operative temperature was recorded in March at 35.55^{0}C. The simulation results revealed that the highest solar gain occurred in December at 2141.14kWh while the lowest solar gain was recorded in August at 1421.90kWh. Figure 12 and 13 show the monthly operative temperature and annual simulation results for case study 2 respectively.

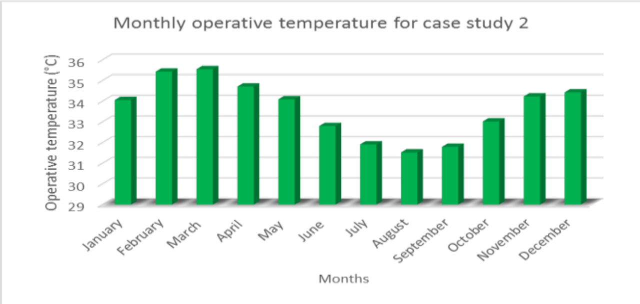

Figure 12. Monthly operative temperature for case study 2

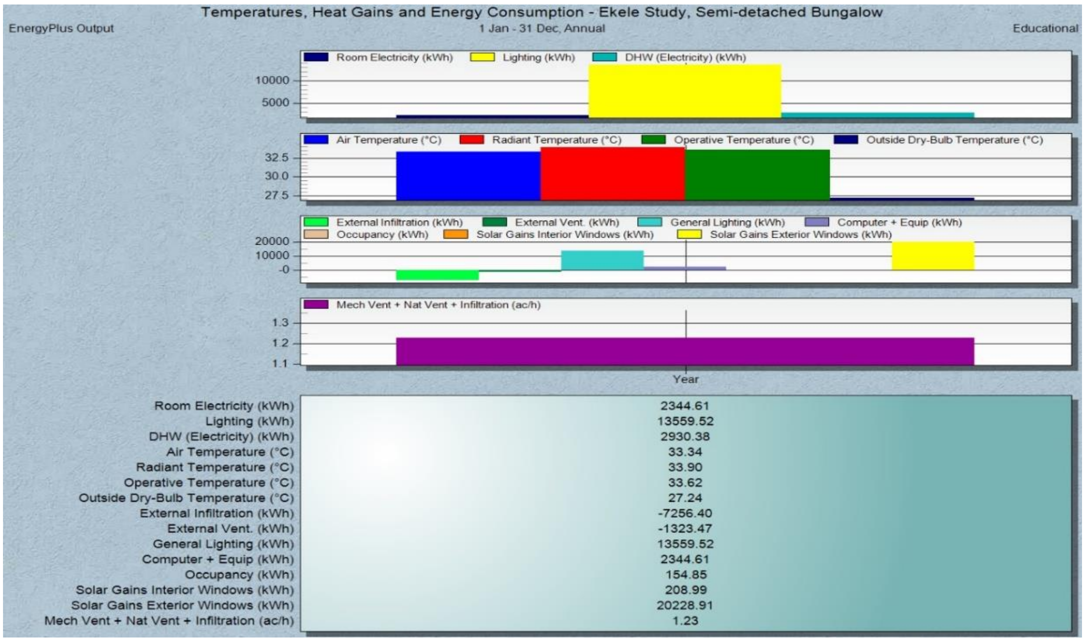

Figure 13. Annual simulation results for case study 2

Case study 3

The lowest operative temperature occurred in August at 31.69^{0}C while the highest operative temperature was recorded in March at 35.62^{0}C. The simulation results revealed that the highest solar gain occurred in May at 3990.06kWh while the lowest solar gains was recorded in February at 2823.59kWh. Figure 14 and 15 show the monthly operative temperature and annual simulation results for case study 3 respectively.

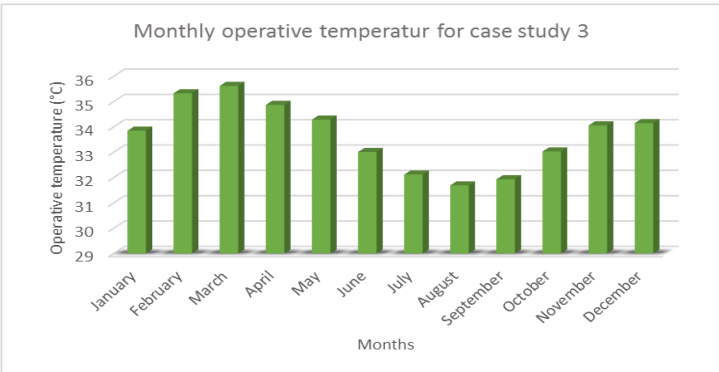

Figure 14. Monthly operative temperature for case study 3

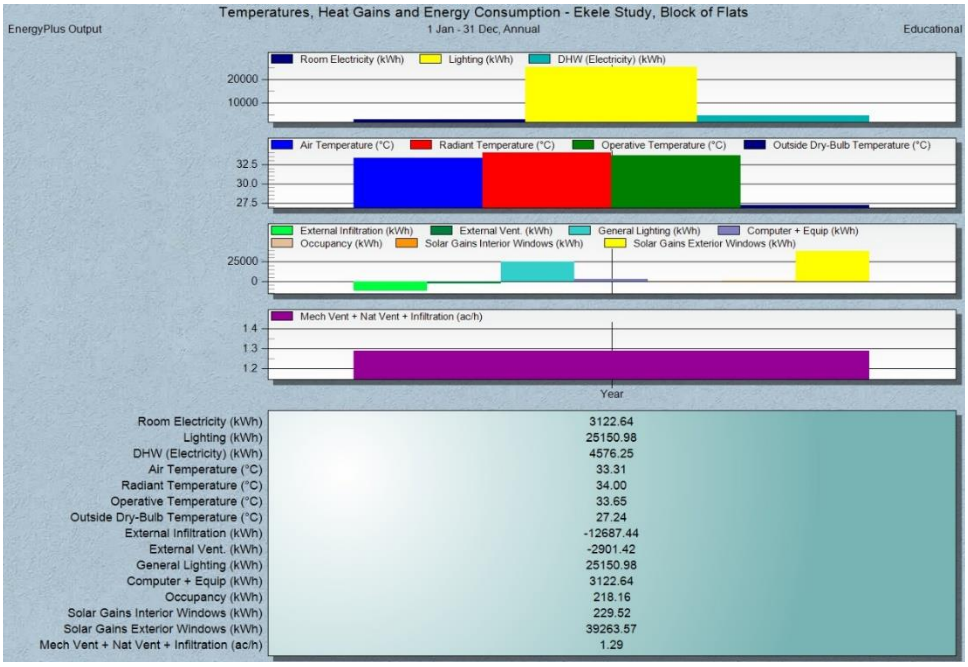

Figure 15. Annual simulation results for case study 3

DISCUSSION

Multiple case study of existing buildings in Lokoja, Nigeria was adopted in this study to understand the similarities and differences if any between the most popular buildings types in the study area particularly regarding thermal comfort. The simulation results of the selected building types revealed that there are no significant differences in terms of thermal comfort. The lowest annual average operative temperature for case studies 1, 2 and 3 were 33.36^{0}C, 33.62^{0}C and 33.65^{0}C respectively. The simulation results for the three case studies showed that case study 1, detached bungalow performed best compared to case studies 2 and 3 in terms of average annual operative temperature. The performance of case study 2, which is a semi-detached bungalow, was better than case study 3, block of flats, especially between the month of March and October. Figure 16 shows the monthly operative temperature of the three case studies.

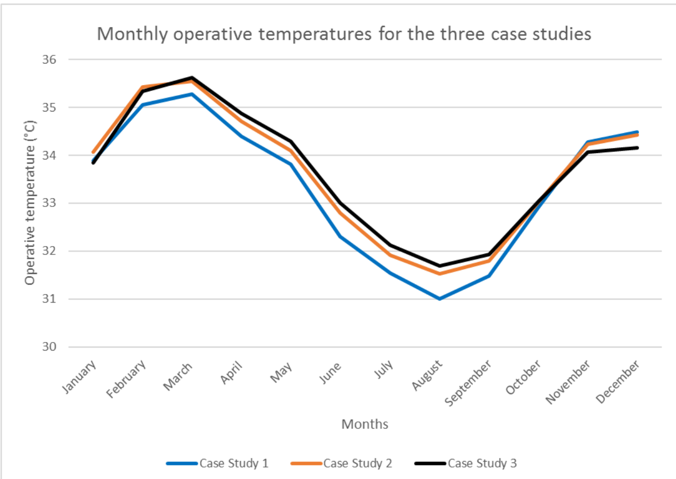

Figure 16. Monthly operative temperature for the three case studies

The total annual solar gains for case studies 1, 2 and 3 were 24118.27kWh, 20497.90kWh, and 39493.09kWh respectively. This showed that case study 3 has the highest total annual solar gains while case study 2 has the lowest. It can be argued from this result that higher solar gains might not mean higher operative temperature. Other factors, which include the area, height and the orientation of the building, may be responsible for this. Figure 17 shows the monthly solar gains for the three case studies.

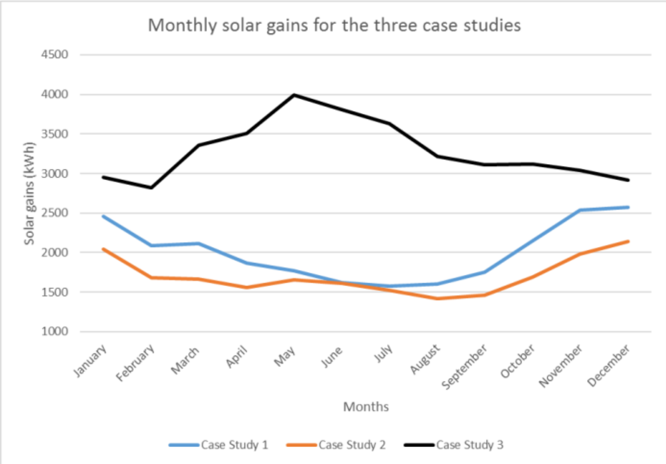

Figure 17 Monthly solar gains for the three case studies

CONCLUSION

The study of the three case studies has shown that there are no significant differences between them in terms of thermal comfort. Although there is a significant difference in terms of solar gains (see figure 17), it does not reflect much in their operative temperatures.

The results also confirmed the level of thermal discomfort in existing residential buildings. It has been established based on ASHRAE Standard 55 that for Nigeria with a monthly mean outdoor temperature of nearly 26^{0}C, 90% of the population will be comfortable at temperatures up to 28^{0}C (GIZ, 2015). Hence, it is obvious from the simulation results that there is thermal discomfort in residential buildings in the study area. Nevertheless, intelligent design, material specifications and construction techniques by design professionals can improve the performances of residential building types. Hence, there is an urgent need for design professionals to improve comfort level in residential buildings and reduce energy demand due to too much reliance on mechanical cooling systems. This will enhance people's wellbeing as result of reduction in energy bills, CO_2 emissions, and environmental pollutions.

This study has provided data that is expected to improve knowledge regarding the thermal performance of some residential building types in the study area and in similar climates.

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