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Effects of Passive Airflow Pattern on Indoor Thermal Comfort of Low-Rise Residential Buildings in The Hot-Humid Climate of Anambra State, Nigeria

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***Abstract*—This study examined the effects of passive airflow patterns on indoor thermal comfort in low-rise residential buildings in the hot-humid climate of Anambra State, Nigeria. The increasing challenges of global climate change and rising energy costs have made passive cooling strategies, such as natural ventilation, a sustainable alternative to mechanical cooling. The research aimed to assess how passive airflow patterns, influenced by window placement, building orientation, and fenestration, impact thermal comfort across different seasons.**

A combination of experimental and survey research methods was employed, focusing on three residential layouts in Obosi, Idemili North Local Government Area. Data were collected from selected spaces in four prototype buildings during the dry and rainy seasons, using multi-functional anemometers and Autodesk CFD software for simulation. The study found significant differences in indoor thermal comfort across seasons, with airflow patterns varying in intensity due to climatic conditions, building orientation, and fenestration design. Natural ventilation can enhance thermal comfort in hot-humid climates, but factors such as building orientation and fenestration design need to be optimized. Improved design strategies for building openings and layouts are recommended to maximize passive airflow and reduce reliance on mechanical cooling systems.

***Index Terms*—passive airflow, indoor thermal comfort, climatic variability, low-rise residential buildings, tropical regions, building orientation, architectural design, Nigeria.**

I. INTRODUCTION

The challenges of climate change and rising energy costs have made indoor thermal comfort in residential buildings increasingly important, especially in hot-humid regions like Anambra State, Nigeria. High temperatures, humidity, and intense solar radiation make it difficult to maintain comfortable indoor conditions, often leading to heavy reliance on mechanical cooling systems that are costly and environmentally unsustainable [1]. As an alternative, passive airflow patterns, driven by natural ventilation, offer a sustainable solution. By harnessing wind and buoyancy forces, natural ventilation can reduce indoor temperatures and improve air quality, contributing significantly to thermal comfort in low-rise residential buildings.

In response to rapid urbanization in African countries, where annual growth rates exceed 5%, housing designs have increasingly shifted toward vertical structures due to land scarcity [2]. However, effective design for thermal comfort must consider how to balance the internal activities of buildings with external environmental conditions [3]. Natural ventilation offers a critical pathway to achieving this balance, as it relies on passive strategies like window placement and size to enhance airflow without the need for mechanical cooling [4]. In hot-humid climates, these design strategies are essential for improving indoor air circulation and thermal comfort [3].

Thermal comfort, which Okeke et al. (2010) [5] describe as the state of satisfaction with the thermal environment, depends on various factors, including geographic location, building structure, and climatic conditions like temperature and humidity. In tropical regions such as Nigeria, maintaining thermal comfort without mechanical cooling is particularly challenging due to increasing energy demands and the effects of global warming [6]. Additionally, poor post-occupancy practices, such as neglecting natural ventilation strategies, and suboptimal building designs exacerbate issues like urban heat islands and poor airflow [7]. This study seeks to address these challenges by assessing how passive airflow patterns can improve thermal conditions in low-rise residential buildings across different seasons in Nigeria.

By exploring the role of natural ventilation in enhancing indoor air quality and thermal comfort, this research aims to contribute to the development of sustainable building practices. The study's findings will inform architects and urban planners on how to optimize building designs to reduce the reliance on mechanical cooling systems, thereby promoting energy efficiency and sustainability in rapidly urbanizing, hot-humid regions [8].

II. RESEARCH METHODOLOGY

The study adopted a combination of experimental and survey research designs, as referenced in the earlier work of Oforji et al., 2023 [1] which focused on airflow patterns in tropical low-rise residential buildings. Groat and Wang (2002) [9] highlighted that, in addition to maintaining the credibility and efficiency of research procedures, this research design is effective in determining causality. The study employed comparative experimental design that involved comparison of two prevailing seasons (events) of the areas of study with the probability of obtaining the same results. It also involved the use of building physics equipment –Autodesk CFD 2018 (Computation Fluid Dynamics) for data analysis. The research population comprised basically of low-rise residential buildings within the designated three layouts of Obosi, Idemili north local government area of Anambra State, South-East Nigeria, which included: Awada, Ugwuagba and Ozalla layouts**.** Figure 1 shows the study area in detail

A. The Survey

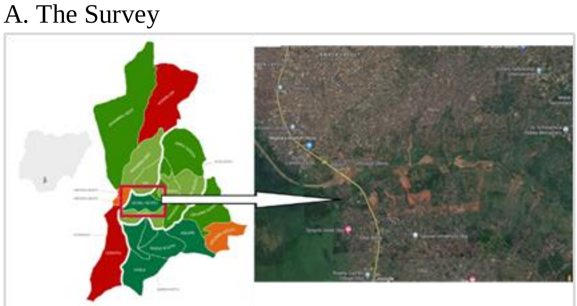

Figure 1: - A map of the obosi Nigeria (srtudy area)

A review of the buildings within the study area highlighted several observations:

1. The area predominantly consists of four-story blocks of flats.
2. These buildings are primarily 3-bedroom flats, with four distinct architectural designs forming the basis for four prototype building types (A, B, C, and D) used in the simulations.
3. The designs incorporate vertical stacking of floors to accommodate the high population density.
4. Common architectural elements include balconies where needed, repetitive prototype floors, and headroom heights that are typically less than 3 meters, leading to variations in the sizes of doors and window openings.
5. There is inconsistency in the building setbacks from property lines, due to non-compliance with local building codes and regulations.

The sampling frame of the study comprised three layouts namely: Awada, Ugwuagba and Ozalla layouts based on the estimated number of low-rise residential buildings from the recorded information of Idemili North Town Planning Authority of the Local Government Area (INTPA).

Table 1-Estimated Number of Low-Rise Residential Buildings at Obosi, Idemili North Local Government Area, Anambra State.

Scheme	Names of Layouts	Estimated number of low-rise residential buildings
1	Awada layout	10,518
2	Ugwuagb a layout	9,529
3	Ozalla layout	7,036
	Total	27,083

Source: Idemili north local government area, town planning authority, Anambra State, 2018.

The estimated total number of low-rise residential buildings in the study area was 27083 and this was the sampling frame for the distribution of questionnaire, because each building occupant was actively involved in the study. Taro Yamane formula was employed to generate the sample size because the population size is finite (known).

B. Using Taro Yamane formula to determine sample size

The derived sample size of the study was 433 determined using Taro Yamane Formula:

$n = \frac{N}{(1+Ne^2)}$ n = sample size, N= population size and e = margin of error = 0.05

Given that our population of low-rise residential buildings is 27083, then

$$n = \frac{27083}{(1+27083(0.05)^2)}$$

$$= \frac{27083}{1+67.7075} = \frac{27083}{68.7075} = 394.1782$$

~ 394.

Using the names of layout as strata and applying proportional allocation, the sub-samples become:

(1) Awada Layout: 10518/27083 x 394 = 153.0145 = 153 approximately.

(2) Ugwuagba Layout: 9529/27083 x 394 = 138.6266 = 139 approximately

(3) Ozalla Layout: 7036/27083 x 394 = 102.3588 = 102 approximately

However, attrition of 10% gave a sample size of 433 for the non-respondents. Then using the names of layout as strata and applying proportional allocation, the sub-samples become:

(4) Awada Layout: $\frac{10518}{27083}$ x 433 = 168.1606 ~ 168

(5) Ugwuagba Layout: $\frac{9529}{27083}$ x 433 = 152.3485 ~ 152

(6) Ozalla Layout: $\frac{7036}{27083}$ x 433 = 112.4907 ~ 112

Table 2**.** Estimated Sample Size of Low-rise Residential Buildings at Obosi, Idemili North Local Government Area, Anambra State, with 5% margin of Error.

S/N	Names of Layouts	Estimated number of low-rise residential buildings	Sample size of low-rise residential buildings with a 5% error margin	Sample size of low-rise residential buildings with attrition of 10%
1	Awada layout	10,518	153	168
2	Ugwuagba layout	9,529	139	112
3	Ozalla layout	7,036	102	153
	Total	27,083	394	433

Source: Idemili north local government area, town planning authority, Anambra State, 2018.

A random sampling method was employed to select four prototype buildings (A to D), comprising two in Awada, one in Ugwuagba, and one in Ozalla, according to the estimated number of buildings (see Table 2). Subsequently, purposive sampling was used to identify a living room, bedroom, kitchen, and balcony on both the ground and fourth floors of the selected prototypes for investigation, based on the availability and willingness of occupants to participate in the study. Over four days in March (dry season) and October (rainy season) of 2018, multi-functional Anemometers TA465 were utilized to gather data on temperature, relative humidity, and wind velocity in the designated spaces. In addition to experimental investigations, modeling and simulation were conducted on the building's openings and fenestrations within the indoor spaces. Instruments such as a magnetic compass were used to observe prevailing wind directions, while a digital camera captured photographs of the selected buildings. The external dimensions and openings were measured using a 30.6m fiberglass tape and a 3.6m metallic tape, and a scientific calculator was employed for data analysis. Additionally, data were collected through a questionnaire that addressed the impact of poorly designed building openings and fenestrations on architectural features in the study area. The responses highlighted (a) ceiling heights, (b) types of window openings, (c) doors as alternatives for airflow in room spaces, and (d) window sizes and airflow patterns. Respondents provided feedback on the effects of the building openings and fenestrations on their thermal comfort at various floor levels.

The questionnaire consisted of 13 questions, featuring both nominal and ordinal structures, and was divided into two sections. The validity of the model and simulation process followed the guidelines set by Fairley (1976). The reliability of the questionnaire was tested using the Cronbach method, yielding a Cronbach alpha value of 0.77, indicating a high degree of reliability and confirming the study's findings. Data analysis was conducted based on the objectives of the investigation, addressing both the research question and hypothesis. The as-built drawing of the selected building, illustrated in Figure 2, was transferred to CAD to support further analysis and simulations.

Figure 1: Plans of the studied low-rise residential building in the area.

C. Validating Autodesk Computational Fluid Dynamics (CFD) data against experimental data.

An example is given with building C on a more detailed simulation approach for validating the accuracy of Autodesk Computational Fluids Dynamics against the experimental data. The temperature calculated from simulation is compared with the temperature measured. The input parameters taken into consideration for model simulation as shown in table 2.1, however the balconies are not considered in the simulation.

Table 2.1-Input parameters for building model

	Parameters for Building C	Input values meters (mm)
1	Building height	3000 mm
2	Window width	1200 mm
3	Window sill height	900 mm
4	Window height	1200 mm

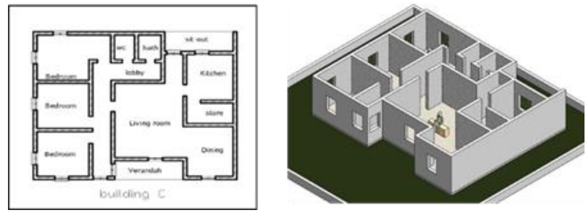

Figure 2.1 Building C floor plan and 3D model in Autodesk Revit 2018

III. TESTING OF HYPOTHESES

Logistic regression analysis was used to test the Hypothesis

Ho1: -Periodic passive airflow pattern does not have a significant effect on the thermal comfort of low-rise residential buildings in the study area

Table 3.1: -Association between the floor of low-rise residential buildings and the type of force of breeze in the building

Floor of the building	The magnitude of the force of the breeze					
	Not at all n (%)	Low n (%)	Moderate n (%)	High n (%)	χ^2	P value
Ground floor	6 (6.6)	38 (41.8)	44 (48.4)	3 (3.3)	9.338	0.674
First floor	4 (4.1)	42 (43.3)	48 (49.5)	3 (3.1)		
Second floor	4 (5.1)	28 (35.9)	45 (57.7)	1 (1.3)		
Third floor	6 (8.1)	21 (28.4)	46 (62.2)	1 (1.4)		
Fourth floor & above	4 (7.4)	20 (37.0)	27 (50.0)	3 (5.6)		

IV. RESULTS

A. Simulation Data of Building Openings Showing the Effects of the Principle of Rhythm

The study investigated, using modeling and simulation procedures, the impacts of outdoor airflow on the building openings and fenestration in the living rooms of the four proto-type buildings in the study area for the effects of the architectural principles of Rhythm on low-rise residential buildings. Using the same simulation parameters and different window sizes and placements, each of the designated buildings

(A–D) was simulated at the ground floor and fourth floor levels. There were relative temperature differences as a result of the convectional impact of wind velocity on the different floors (see Tables 6 and 7).

Table 4. Simulation Data for building openings and fenestration showing effects of architectural principles of rhythm in Building "A" (ground floor)

V. DISCUSSION

The results of this study indicate a significant relationship between passive airflow patterns in building openings, fenestration, and the indoor thermal comfort of low-rise residential buildings in the hot-humid climate of Anambra State, Nigeria. This was analyzed through simulations based on data collected from the designated buildings (A-D), which examined the variations in building opening sizes and window dimensions. The simulation process revealed differences in indoor temperature levels, particularly across different floors, with ground floors generally exhibiting higher temperatures compared to top floors. These findings are consistent with previous studies that examined the correlation between airflow patterns and indoor thermal comfort, such as those by (Oforji et al., 2021) [1], (Mba et al., 2023) [3], (Karava et al., 2011) [10], and (Conceição, 2019) [11]. These studies confirmed the impact of airflow on maintaining comfortable indoor environments, particularly in non-air-conditioned buildings. Jamaludin et al. (2014) [12] also emphasized the need to assess indoor temperature variation over specific seasons to identify uncomfortable thermal periods.

The objective and hypothesis of this study were further validated by responses from the questionnaire (see Table 4.6), which highlighted how variables such as building height, floor levels, and openings influence indoor experiences. This aligns with previous studies, such as those by Lui Bau-show et al. (2013) [13], which demonstrated that effective indoor thermal performance depends on design variables like building orientation, height, and the placement of shading devices. Meakhail (2013) [14] also noted that architectural design complexity can cause airflow turbulence, leading to varied indoor comfort levels.

The Categorical Regression Analysis (CATREG) confirmed that the height of the building, floor location, and the size of fenestrations play a significant role in determining the intensity of indoor airflow and, subsequently, indoor thermal comfort. The analysis revealed that building height has the greatest impact on indoor airflow velocity and temperature changes, thus enhancing the synergy between architectural design and the environmental climate in ensuring adequate ventilation. This finding echoes the work of Fanger (1970) [15] and ANSI/ASHRAE standard 55 [16], which assert that improving indoor air quality and thermal comfort is dependent on this architectural-environmental interaction. Wang et al. (2012) [17] also advocated for natural ventilation as an efficient method to reduce energy consumption while maintaining thermal comfort.

In line with studies by Ayata [18], Nwalusi et al. (2022) [19], Okeke et al. (2019) [5], and others, the results suggest that natural and hybrid ventilation strategies can make buildings more energy-efficient, particularly in tropical climates. Additionally, the use of passive airflow patterns and proper fenestration design enhances both sustainability and indoor comfort, as demonstrated by previous researchers like (Mba et al., 2023) [3], who emphasized cross-ventilation and the control of building openings for airflow regulation.

The findings of this study also support the importance of appropriately designed building openings and fenestrations in low-rise residential buildings to improve airflow and maintain thermal comfort. Key elements such as floor height, window size, and balcony placement must be adequately considered, especially in the tropical climate of Anambra State, to avoid interference with airflow by surrounding buildings.

Overall, the study highlights the significance of passive airflow patterns in low-rise residential buildings. By considering factors such as window-wall ratio, shading devices, and building orientation, it is possible to improve indoor air circulation, reduce indoor temperatures, and create a healthier and more comfortable environment for occupants. This conclusion aligns with earlier studies that focused on the challenges of maintaining indoor air quality and thermal comfort in tropical regions (Spiru & Simona, 2017 [20]; Kelly & Fussel, 2019 [21]; Vornanen-Winqvist et al., 2018 [22]).

VI. CONCLUSION & RECOMMENDATIONS

The findings of this study demonstrate the significant influence of passive airflow patterns on indoor thermal comfort in low-rise residential buildings within the hot-humid climate of Anambra State, Nigeria. The analysis confirmed that factors such as building height, the size and design of openings, fenestration placement, and floor location play critical roles in airflow distribution, which directly impacts the indoor thermal environment. It was observed that upper floors typically experience better airflow and lower indoor temperatures compared to ground floors, underscoring the connection between airflow velocity and temperature variations with these architectural elements.

These results align with existing research, emphasizing the importance of natural ventilation strategies in achieving thermal comfort, especially in non-air-conditioned buildings. By facilitating natural airflow through strategically positioned openings, buildings can achieve better thermal regulation while reducing energy consumption. The study highlights the need for architects and designers to prioritize passive design solutions in regions like Anambra State, where challenging climatic conditions demand sustainable and energy-efficient building performance.

To enhance indoor thermal comfort through passive airflow, architects should optimize building openings and fenestration designs by carefully considering the size, orientation, and placement of windows to encourage cross-ventilation. Designing buildings that cater to specific climatic needs is essential, especially in hot-humid environments, where passive cooling strategies, such as shading devices and proper building orientation, can reduce solar heat gain. Floor planning should also promote cross-ventilation by ensuring unobstructed airflow through aligned windows and doors, particularly between opposing facades.

In certain conditions, especially during extreme weather, hybrid ventilation systems that combine passive and mechanical strategies may be necessary to ensure adequate airflow when natural ventilation is insufficient. Regular maintenance of windows, doors, and shading devices should be conducted to maintain the effectiveness of passive airflow systems. Additionally, future design modifications may be required to adapt to changing climatic conditions and evolving building needs.

By adopting these strategies, low-rise residential buildings in Anambra State and similar climates can achieve a sustainable balance between passive airflow and indoor thermal comfort, reducing the dependence on mechanical cooling systems and fostering long-term energy savings.

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