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Optimization of Indoor Thermal Comfort and Energy Efficiency in Building

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ABSTRACT

Significant portion of the energy consumed in buildings is dedicated to maintaining indoor thermal comfort. This denotes an increased reliance of buildings on mechanical systems that are dependent on electricity generated from fossil fuels. This issue indicate that the building sector is one of the main contributors to both environment global warming and the energy crisis. Therefore, this paper reports on the optimization of indoor thermal comfort and energy efficiency in building using questionnaire and physical measurement. The research methodology implemented was based on a comparative approach that quantifies the energy consumption and the thermal conditions generated in buildings operating on natural ventilation, hybrid ventilation, and mechanical ventilation respectively. The Analysis of Variance (ANOVA) test conducted at 95% confidence level showed that there was significant difference between the indoor thermal comfort and energy efficiency in natural, hybrid ventilation, and mechanically ventilated building thus: $F=34.335$; $p=.000$. The result shows that the optimization of indoor thermal comfort and energy efficiency in building is influenced by ventilation design variables. This fact emphasizes the imperative need to improve design of natural ventilation in building to achieve optimum comfort and energy savings. Recommendations were made in order to reduce energy use and costs, and to reduce greenhouse gas emissions, through the design of energy efficient buildings.

Keywords: *Energy Efficiency, Energy Saving Strategies, Global Warming, Indoor Thermal Comfort, and Ventilation.*

1. Introduction

Thermal comfort has become an important element in the design, construction, and remodelling of buildings, as well as in the understanding of human behaviour that considers inhabitants' mental conditions (Atolagbe, 2014; Olanipekun, 2014). Thermal comfort has been defined as a mental condition of satisfaction with the thermal environment (ANSI/ASHRAE, 2017). On the other hand, climate-responsive design allows the creation of a structure intrinsically connected with building location, using responsive technologies to improve the performance of buildings (Beesley et al., 2006). Furthermore, indoor thermal comfort cannot be neglected in buildings' design. The thermal comfort concept is heterogeneous, and efforts have been made to define it. Nevertheless, the two aspects of environmental comfort and satisfaction, as well as cognitive performance, health, and productivity, emerge in the building context (Hanc et al., 2019). Therefore, a good definition of thermal comfort regards it as the combination of feeling good and functioning well in comfortable thermal environment (Ruggeri et al., 2020). As a result, these have contributed to use of artificial means to provide a comfortable thermal environment at high energy consumption in building (Atolagbe, 2014; Olanipekun, 2014). This fact emphasizes the imperative need to improve climate building design to achieve both optimum comfort and energy savings.

2. Literature Review

The dependency on energy consumption is increasing exponentially as well as global warming. Altogether, all factors are important in users' perceived satisfaction with built spaces and are directly related to energy consumption, due to the negative effects of rapid urbanization and global warming that have also influenced the deterioration of air quality (Toe & Kubota, 2013; Guo et al., 2022). This sector is responsible for more than 40% of the total energy consumption, and consequently it is the major producer of global greenhouse gas emissions (Hernández et al., 2014). In this complex framework, ventilation has a key and fundamental role, since it has high impact on both buildings' energy consumption and Indoor thermal comfort. Depending on the ventilation technique, which can be used in combination with other passive solutions such as the use of thermal inertia for night cooling and shadings to avoid solar heat peaks, the carbon footprint can be consistently lowered (Salcido et al., 2015; Carrilho &Linden, 2016; Chenari et al., 2016) Moreover, ventilation choice cannot overlook the well-being of users', which needs to be the primary aim of indoor design (Carrilho &Linden, 2016). Generally speaking, ventilation techniques can be divided into three main groups: natural ventilation, mechanical ventilation, and hybrid or mixed mode ventilation. Each of these categories has different implications on energy consumed and comfort. Natural ventilation, totally relying on natural forces (wind or buoyancy-driven), can consistently lower buildings' carbon footprint (Etheridge, 2011; Passe & Battaglia 2015; Krarti, 2018). Moreover, the acceptable range of thermal comfort was noticed to be enlarged when natural ventilation is present, with higher acceptance of high indoor temperatures when outdoor temperatures are high too (De Dear & Brager, 2022). This led to the introduction of the adaptive model for naturally ventilated buildings on ASHRAE Standard 55, which is now used together with Fanger's model in naturally ventilated buildings (Fanger, 1970; ANSI/ ASHRAE, 2017).

Conversely, the possibility to fully regulate temperature, airflow, and air velocity is a clear advantage of mechanical ventilation, of which performance is perfectly predictable and controllable if compared with natural ventilation, with positive implications on the indoor thermal comfort (Lee, 2011). Finally, hybrid ventilation can be a good compromise between the two techniques, guaranteeing energy savings, but exploiting mechanical ventilation when proper indoor thermal comfort conditions cannot be met with natural ventilation, only (Chen et al., 2018; Abdul et al., 2020). In this framework, ASHRAE recommended to use natural ventilation, only in homes where mechanical ventilation or air-purifiers were not installed, in order to avoid thermal discomfort (ANSI/ ASHRAE, 2017).

A recent study by Aycam et al. (2020), stated that half of the energy in the buildings is used by mechanical ventilation systems to provide comfort. This energy is essentially electric, so the contribution of building sector electricity use to total electricity consumption is even higher. Otherwise, due to major transformations in living standards and the raising of the building users' comfort requirements, such as electric lighting, air conditioning, and other appliances. Residential demand for electricity is expected to be boosted. As a consequence, the energy supply deficit consumed by air conditioning systems is estimated to double by 2030 (Nachmany et al., 2015). In order to reduce energy use and costs, and to reduce greenhouse gas emissions, buildings continue to be targeted through energy efficient retrofits. One of the largest energy consumers in buildings in warm humid climate is the cooling system (Krarti, 2018). Hence minimizing cooling energy usage and enhancing its efficiency will be crucial for reducing emissions and achieving the climate change targets set by Governments around the world (Chen et al., 2020).

The main reason for indoor thermal discomfort and high energy consumption is related to inefficient design of the building's envelope, including: wrong orientation, improper glazing area with no shading devices, low-quality materials (Yu et al., 2020). The building's energy demand is directly associated with the efficiency of its envelope. The building envelope consists of structural materials and finishes that enclose space, separating inside from outside. This includes walls, roofs, openings (windows, doors), and all the surrounding exterior surfaces of a building that provide protection to the users' (Krarti, 2018; Yu et al., 2020). Design features and material properties of the envelope can significantly lower the building's energy consumption. Furthermore, the climate is one of the most important factors affecting the envelope's design in terms of thermal comfort and energy efficiency. Different climates (hot and dry, warm-humid, temperate, or cold) will suggest different design strategies. Specific designs and materials can take advantage of or provide solutions for the given climate, while the building's envelope design can affect 20–60% of the building energy input, making it crucial for achieving energy efficiency (Al-Obaidi et al., 2014; Yu et al., 2020).

3. Research Methodology

The study area is Asaba the capital city Delta State, located in the warm humid climate zone of Nigeria. The research methodology implemented is based on a comparative approach that quantifies the energy consumption and the thermal conditions generated in residential. Three buildings were investigated, while operating on mechanical ventilation system (Air conditions switched-On and windows closed), and the natural ventilation system (Air conditions switched-Off and windows opened) respectively. To examine the effectiveness of the natural ventilation design techniques, in terms of optimization of indoor thermal comfort and energy efficiency with special references to warm humid climatic conditions. The study applied questionnaire survey research and physical measurement. Hence the study was divided into two parts: the first part was carried out through direct physical measurements by using sensors (data logger) to monitor indoor air temperatures, relative humidity, and air velocity which was used to identify the frequency of indoor comfort temperature range. The essence of physical measurement is to represent, and predict causal effects. The second part was carried out through obtaining data from the questionnaire survey to access the effect of indoor thermal comfort of the users' (room temperature) on energy efficiency (ventilation system) in buildings.

3.1 Method and Apparatus:

The measurement was carried out in phases in building A, B, and C, respectively. Phase (1) mechanical ventilation system were on (air-condition). Phase (2) hybrid ventilation system was on (Fans) but AC was off with windows open. Phase (3) natural ventilation system (air-condition and fans off) windows left open. The multi-purpose Air Flow Digital anemometer (AM-4812-2-2) was used to measures air velocity, air flow, and Data logger (TA298) air temperature & humidity. The system collected concurrent physical data: air temperature, air flow and air velocity. The instruments were placed at 0.6m, 0.9m, and 2.1m from the floor to record the thermal comfort variables simultaneously, as the subjects filled in the thermal comfort questionnaire. The data logger was set to acquire data at 60-min intervals. The readings were recorded in separate data sheets. All the completed questionnaires and data sheet entries were given serial numbers for easy identification and synchronization. The readings were transferred onto the corresponding questionnaires at the end of every survey day. Mean radiant temperatures were calculated based on the equation provided by the ASHRAE standard 55. The measuring apparatus for field study and data documentation is shown in Table 1.

Apparatus	Description
	**LUTRON Thermo-Anemometer (AM4201A):** it measures air velocity, air flow and air temperature respectively. Air velocity range is 0.40-45m/s, resolution of 0.001m/s and recording accuracy of ±(3%+0.20m/s). Air flow range is 0 to 9999m3/min, resolution of 1, and recording area of (0 to 9.999m2). Air temperature range is -10oC–60oC, resolution of 0.1oC and recording accuracy of 2.0oC respectively.
	**Data logger (TA298):** recording temperature from 0oC to 50oC and relative humidity from 10% to 99%. The accuracy of temperature reading is between ±1oC. The accuracy for relative humidity is ±5%RH. The reading resolution is 0.1oC for temperature and 0.3% for relative humidity.

The electricity bill was considered for the period of natural ventilation (5 January, 2023 to 8 March, 2023), hybrid ventilation and mechanical ventilation, respectively in order to record the energy consumption. While the instruments recorded the indoor thermal environmental conditions, the researcher observed and kept track of the users' behaviour or activities, such as the opening and closing of windows Figure 1. The monitored buildings are shown in Plate 1 (building A), Plate 2 (building B), and Plate 3 (building C).

Plate 1: [A] Five Bedroom Duplex at GRA, Asaba (Field work,

Plate 2: [B] Five Bedroom Duplex at GRA, Asaba (Field work, 2023).

Plate 3: [C] Five Bedroom Duplex at GRA, Asaba (Field work, 2023).

3.3. Data Presentation:

The data generated from the various sources were sorted and arranged in a way that is adequately fit for statistical analysis and interpretation using tables, bar charts, graphs, frequency distributions and percentages. Table 2; shows data on electric energy consumption distribution from 5 January, 2023 to 8 March, 2023. The energy consumption during mechanical ventilation (Air-Condition is ON and windows closed), hybrid ventilation (AC OFF and Fan ON with windows open), and Natural ventilation (AC and Fan OFF with windows open) in monitored buildings are shown in Figure 2.

Table 2: Ventilation Type and Energy Consumption Distribution

Ventilation Type	Building (A)	Building (B)	Building (C)
Natural Ventilation	10.55	10.5	10.05
Hybrid Ventilation	27.53	30.51	20.25
Mechanical Ventilation	58.05	65.05	40.45
Total	**96.13**	**106.06**	**70.75**

Source: Field work (2023).

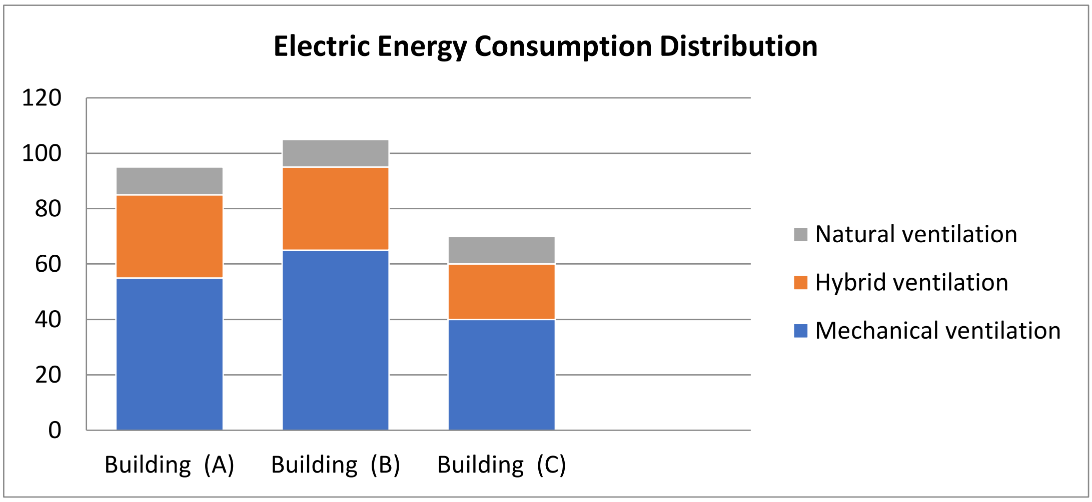

Figure 2: Energy Consumption (Field work, 2023).

Indoor thermal measurements indicate that indoor air temperatures range was 20–35ºC. The values of mean radiant temperature were typically slightly higher than those of air temperature, with differences of 0.2–1.0ºC. The humidity varies from 60% to 90%. Mean indoor air velocity was 0.19 *m/s*, ranging from 0.1–0.5 *m/s*. The frequency of the indoor environment parameters (temperature and relative humidity) are shown in Figure 3.

Questionnaire: How the occupants feel with the indoor temperature during in the naturally ventilated building

This question was asked to know how the respondents feel with the indoor temperature in naturally ventilated building which has the lowest energy consumption rating as shown in Figure 2 above. The Table 3; shows how the occupants feel with the indoor temperature. The result has shown that about 3.07% of the respondents feel cold, 1.53% feel cool, 4.61% feel slightly cool, 1.53% feel neutral, 61.53% feel slightly warm, 6.15% feel warm and 21.53% feel hot. This shows that more of the respondents feel hot as shown in Figure 4.

Table 3: Occupant feeling with the indoor temperature

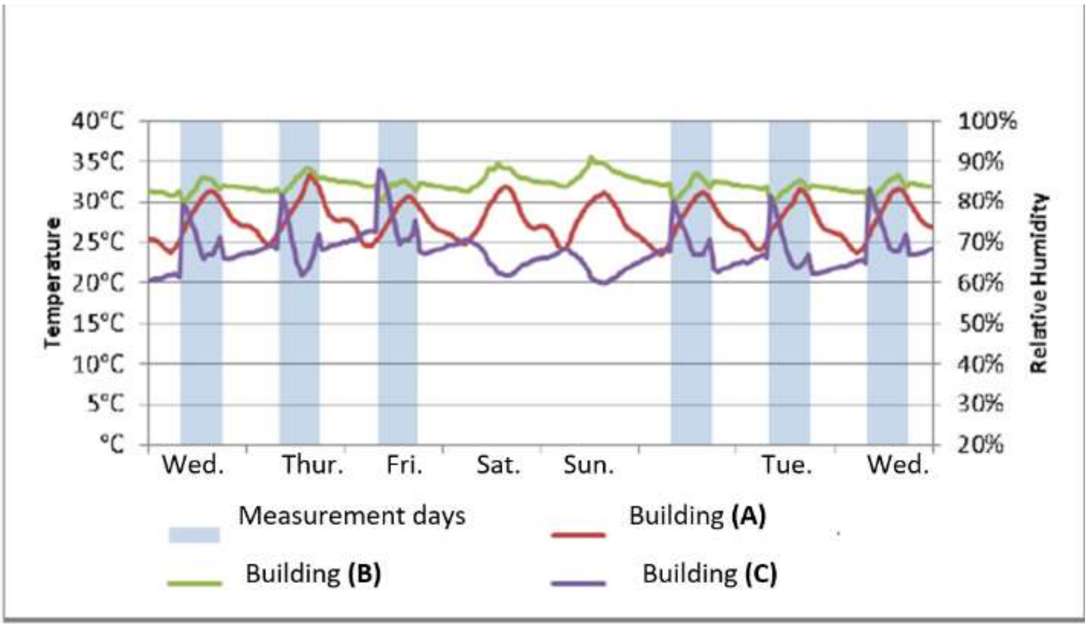

Figure 3: The temperature and relative humidity distribution (Field work, 2023).

Questionnaire: How the occupants feel with the indoor temperature during in the naturally ventilated building

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Table 3: Occupant feeling with the indoor temperature

Occupant feeling with the Indoor temperature	frequency	percentage
Cold	2	3.07%
Cool	1	1.53%
Slightly cool	3	4.61%
Neutral	1	1.53%
Slightly warm	40	61.53%
Warm	4	6.15%
Hot	14	21.53%
Total	**65**	**100%**

Source: field work (2023).

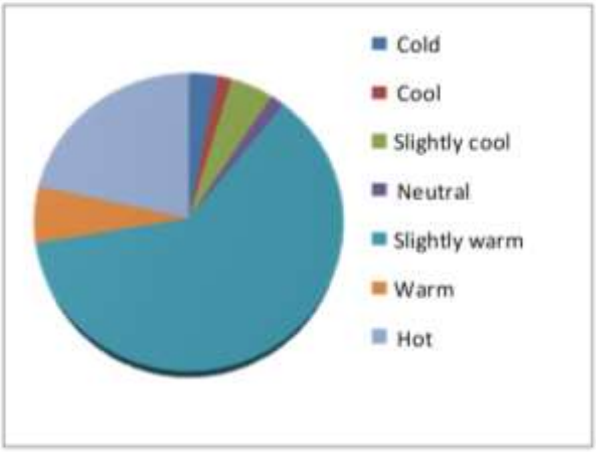

Figure 4: Occupant feeling with the indoor temperature (Field work 2023).

The result in Table 4 has reported the p-value result for the ANOVA analysis between optimization of indoor thermal comfort and energy efficiency in building. The result is said to be significant if p-value is less than 0.05 significant level. The result reports a p-value of 0.000 with an F-value of 34.335. We therefore reject the null hypothesis and accept the alternate hypothesis stating that the window configuration significantly differ natural ventilation performance of residential buildings in Onitsha, Nigeria.

Table 4: The ANOVA result between various window configuration and natural ventilation performance

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.027	4	.257	34.335	.000
Within Groups	2.693	20	.135		
Total	3.720	24			

Source: ANOVA analysis output, SPSS 25

4. Discussion of Results

This research on optimization of indoor thermal comfort and energy efficiency in building is a key factor in the field of sustainable design, and climate-responsive design, as energy savings strongly depend on ventilation techniques. The choice of proper ventilation type cannot be made regardless of indoor comfort and well-being.

The result in Table 2 has reported the ventilation types, energy consumption distribution and comparative analysis of natural ventilation, hybrid ventilation, or mechanical ventilation respectively. It indicated that the natural ventilation had the lowest energy consumption rating followed by hybrid ventilation, and mechanical ventilation had the highest energy consumption rating.

5. Conclusions

This research aims at providing an overview on the comparison of conditions for optimization of indoor thermal comfort and energy efficiency in building provided by different ventilation types. For this reason, it was chosen to include only papers comprising and treating the types of ventilation, in order to highlight the points in common and differences in the indoor conditions and energy savings provided by each ventilation technique. The use of either natural ventilation, hybrid ventilation, or mechanical ventilation is highly dependent on the climate, the building type, and the season. This fact emphasizes the imperative need to improve design of ventilation in building to achieve optimum comfort and energy savings. Use of natural ventilation potentially reduces the operational and the maintenance cost needed for mechanical system, the space needed to accommodate it and the embodied energy. Apart from providing both good indoor air quality and acceptable thermal comfort, natural ventilation can also contribute to improve a building's energy efficiency. Although, it should be mentioned that the hybrid ventilation systems will still require the mechanical equipment. The findings indicated that "average overall energy consumption of air conditioned buildings is approximately twice that of similar sized naturally ventilated buildings" and that making the most of natural ventilation is a simple and cost-effective way of achieving big savings.

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