PAPER 103 - PARAMETRIC STUDY ON NATURAL VENTILATION: A CASE STUDY OF ENGINEERING CENTRAL WORKSHOP, FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

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ABSTRACT
This study provides a literature review on natural ventilation principles, factors affecting airflow, thermal comfort, and the use of Computational Fluid Dynamics (CFD) in building design. The researchers created a detailed 3D model of a workshop and conducted simulations using the DesignBuilder-EnergyPlus software suite. The simulations focused on thermal comfort and were performed on a baseline model with a window-to-wall ratio (WWR) of 30%. The results showed that occupants experienced thermal discomfort for 30.74% of the year, with the remaining 69.26% being comfortable, ranging from "hot" to "slightly warm" sensations. The study then explored the impact of different interventions. Implementing lighting control improved thermal comfort, resulting in a 1.37% increase in the number of hours occupants experienced comfort. The introduction of mechanical ventilation without cooling had a minimal impact on thermal comfort (1.17% improvement). However, when mechanical ventilation and scheduled cooling were combined, there was a significant improvement. The predicted thermal sensation ranged from "slightly warm" to "slightly cool," with most occupants experiencing "neutral" conditions. This strategy increased comfort hours by 14.62% compared to the baseline. While lighting control and mechanical ventilation with fans offered minimal benefits, the combination of mechanical ventilation and scheduled cooling significantly enhanced occupant comfort.

KEYWORDS: natural ventilation, Computational Fluid Dynamics (CFD), thermal comfort, sensational vote, simulation

1. INTRODUCTION

Indoor natural ventilation has gained significant attention in recent years as an energy-efficient and sustainable approach to providing fresh air and maintaining optimal indoor air quality.

This article by (Santamouris *et al*., 2020) provides a comprehensive review of passive cooling technologies in urban buildings, with a focus on the feasibility of using natural wind for maintaining indoor thermal comfort. The review discusses various strategies and techniques, such as natural ventilation, wind catchers, and wind-driven ventilation systems. It explores the advantages, challenges, and potential applications of these technologies in densely populated areas. The article also examines case studies and simulation studies to evaluate the effectiveness and energy efficiency of using natural wind for indoor cooling. These studies found that the popularity of natural ventilation depends on the climate.

Numerous studies conducted in the last five years have demonstrated the benefits of natural ventilation in various building types, including offices (Zemei *et al*., 2019), educational facilities (Montazeri and Azizkhani, 2018), and residential buildings (Saadatian *et al*., 2019). However, (Yang *et al.,* 2019) provide a comprehensive review of thermal comfort in indoor environments with non-uniform air temperature and air velocity distributions. It specifically focuses on the impact of uneven distribution on occupants' perception of thermal conditions. The review incorporates findings from both computational fluid dynamics (CFD) simulations and field measurements. Several studies have explored the application of CFD modelling in the context of indoor natural ventilation. For example, Liu *et al.* (2018) conducted a CFD simulation to investigate the natural ventilation performance of a multi-storey office building. The study examined the influence of window configurations, wind directions, and wind speeds on airflow patterns and thermal comfort. The findings indicated that specific combinations of window openings and wind directions could significantly improve indoor air quality and thermal conditions.

The research is focused on developing a comprehensive understanding of the airflow patterns and thermal comfort conditions and using this information to identify and evaluate design strategies that can improve indoor air quality and energy efficiency. The ultimate goal is to provide architects, engineers, and building owners with practical guidelines for designing effective and sustainable natural ventilation systems. However, the application and performance of natural ventilation strategies in workshop environments, such as the Engineering Central Workshop at the Federal University of Technology, Minna, have received limited attention. Workshops often present unique challenges due to their specific operational requirements, high heat loads from machinery and equipment, and variable occupancy patterns (Holman, 2020). These factors can significantly impact the effectiveness of natural ventilation strategies, necessitating a comprehensive understanding of the parametric factors influencing their performance.

The aim of this research is to carry out a parametric study on natural ventilation for the case of the engineering central workshop, Federal University of Technology, Minna. This will be achieved via the following objectives: to establish the pattern of the natural ventilation of the workshop, re-design a better ventilation pattern for the workshop and evaluate and compare the results of the redesign to that of the original workshop design.

This study is justified by the challenges posed by excessive heat within the workshop, which can adversely affect the working environment, productivity, and occupant comfort, prompting for lot of questions which this research intends to address.

2. THEORETICAL ANALYSIS

Thermal comfort models and indices

To assess and quantify thermal comfort, numerous models and indices have been developed. One widely used model is the Predicted Mean Vote (PMV) index, proposed by Fanger (1970), which calculates the average thermal sensation vote based on the predicted thermal sensation of occupants. The PMV index considers six primary factors that affect thermal comfort which are air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate. The resulting thermal sensation is classified on a seven-point scale from "cold" to "hot." Other indices, such as the Adaptive Thermal Comfort (ATC) model (ASHRAE, 2017), take into account the adaptive behaviours of occupants in response to changing environmental conditions.
Based on the state of an ambient environment, Carrilho da Graça (2017), provides a comprehensive review of thermal comfort models. It discusses the different approaches and categorizes thermal comfort models into static and dynamic types. These cover the underlying principles, parameters, and methodologies used in each type of model. It also discusses the advantages, limitations, and applications of static and dynamic thermal comfort models. Cheung and Rao (2018), discuss various models commonly used to assess thermal comfort, including the PMV model and the Adaptive Thermal Comfort model. The authors examine the Predicted Mean Vote (PMV) model, which is widely used for predicting thermal comfort based on factors such as air temperature, humidity, clothing insulation, metabolic rate, and air speed. The PMV model can then be applied to these simulations to predict the thermal sensation of occupants and identify potential areas of discomfort. This integration allows for iterative design optimization to achieve better thermal comfort conditions (Li *et al.,* 2021; Yao *et al*., 2019).
The PMV index has a seven-point scale (Table 1) for participants to express thermal sensations under given thermal environments.

Table 1: Seven-point thermal sensation scale (Fanger 1970)

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
– 3	– 2	– 1	0	1	2	3

The relationship of the PMV index to the imbalance between actual heat from the body and the heat required for thermal comfort at a specified activity in a given thermal environment can be described by the following equation.

$$PMV = (0.303e - 0.036M \ + 0.028) \qquad 1$$

Where M is the metabolic rate and L is the thermal load defined as the difference between the internal production of heat and heat loss to the actual environment.
However, there are discrepancies between the PMV prediction and the actual mean vote (AMV) of occupants in buildings (Kim *et al.* 2015).
To overcome these limitations, an adaptive predicted mean vote (aPMV) model, as shown in Eq. (2), was proposed by Chen *et al*. (2020) to introduce an adaptive coefficient into the PMV model based on the black box theory:

$$= \ \mathrm{PMV}/((\mathrm{PMV}\ 1 + \lambda \times \mathrm{PM})) \qquad 2$$

where λ is an adaptive coefficient which considers culture, climate, social, psychological and behavioural adaptations.
Since the metabolic rate is difficult to measure or estimate, it is normally assumed to be constant for some specified activities in the PMV model Gilani *et al*. (2016)
The activity level can be modified to improve the accuracy of the PMV model.

$$M = 0.1092 \times (MPA \times 0.0296) \qquad 3$$

where MPA is the mean arterial blood pressure.

Li and Zhang (2018) provide a comprehensive review of the evaluation of thermal comfort in naturally ventilated buildings, specifically addressing the limitations of using PMV. The review critically examines the challenges and discrepancies associated with using PMV to predict the mean comfort votes of a group of people in everyday building conditions, so PMV model was improved with the following equation.

$$PMVnew = 0.8 \times (PMV - DPMV) \quad (4)$$

Where $DPMV$ is the deviation correction function associated with indoor and outdoor climates and 0.8 is the regression coefficient.

3. METHODOLOGY

The study on natural ventilation design involves the use of computational fluid dynamics (CFD) modelling to determine the best design parameters for achieving better ventilation in an indoor environment (Engineering Central Workshop, Federal University of Technology, Minna). To achieve this, the following are the materials and methods that will be employed for this process:

Materials

i. Computer with Designbuilder incorporated with Computational Fluid Dynamics (CFD) Software (EnergyPlus)
ii. Building Information/Geometry: (Federal University of Technology, Mechanical Workshop)
iv. Climate Data
vi. Ventilation System Specifications parameters such as window dimensions, opening types, ventilation rates, and control strategies.
v. Tape rule

Methods

i. **Assessment of the case study components and external environment**.
This involves conducting a thorough assessment of the case study components, which includes the Engineering Central Workshop building itself and its surrounding environment. This assessment involves evaluating the building's construction materials, architectural design, existing ventilation systems, and outdoor conditions such as wind patterns and solar exposure. Understanding these factors is crucial for identifying potential areas of improvement and determining the baseline conditions for the subsequent analysis.

ii. **Modelling of Central Engineering workshop building baseline model**
A baseline model of the Central Engineering Workshop building was created. This model serves as a representation of the building's geometry and characteristics, including its layout, dimensions, windows, openings, and other relevant features. The model was developed using DesignBuilder software tools.

iii. **Thermal comfort analysis of the baseline model**
Thermal comfort analysis was conducted with the aid of EnergyPlus software. This analysis aims to evaluate and quantify the thermal comfort conditions within the building. Various parameters such as indoor air temperature, humidity, air velocity, and radiant temperature are assessed against established comfort metrics. The analysis helps identify any potential thermal discomfort issues within the building under the existing conditions.

iv. **Simulation of the different improvements in thermal comfort strategies.**
Simulations were performed to assess the impact of different natural ventilation efficiency improvement strategies and building thermal comfort strategies. These simulations involve altering parameters such as Lighting control, Mechanical ventilation without cooling, and Mechanical ventilation with cooling, as well as incorporating airflow control mechanisms. The simulations help evaluate how these strategies affect the ventilation performance and thermal comfort conditions within the building. The strategies to improve natural ventilation efficiency and corresponding thermal comfort were then simulated.

4. RESULTS AND DISCUSSION

Figure 1: South orientation of the building 3D model

Figure 2: Building main facade and surroundings

Figure 1, presents the 3D model geometry and layout of the engineering central workshop FUTMinna, with a total floor area of 1230m^3 while Figure 2, contains the main building workshop façade and its environment.

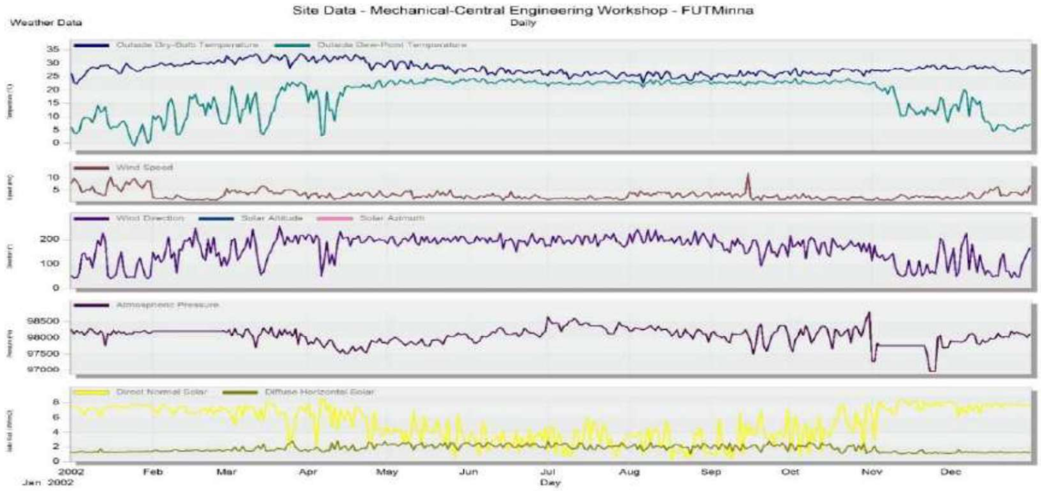

Figure 3: Site data (1 Jan – 31 Dec) for zone conditions reported for an occupied period

Figure 3: shows site data (outside dry-bulb temperature, outside dew-point temperature, wind speed, wind direction, solar altitude, solar azimuth, atmospheric, direct normal solar and diffuse horizontal solar energy) reported for occupied periods only with a maximum outside dry-bulb temperature of 31.88 ^{o}c in the month of March and a minimum of 25.21 ^{o}c in August. The maximum outside dew-point temperature is 23.46 ^{o}c in the month of April and the minimum is 8.88 ^{o}c in January. Wind speed reaches a maximum of 11.98m/s during the month of September and a minimum of 2.25 m/s in May, while the maximum atmospheric pressure is 98386.23 Pa during the month of July and the minimum of 97656.21Pa experienced in November. Direct normal solar energy amounting to a maximum of 232.26 kWh is experienced in December and a minimum of 82.95 kWh in August, while the maximum diffuse horizontal solar energy is 69.7 kWh in May and a minimum of 37.8 kWh in November.

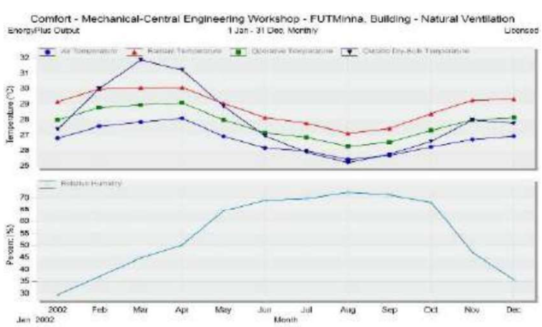

Figure 4: Comfort data - (Baseline model)

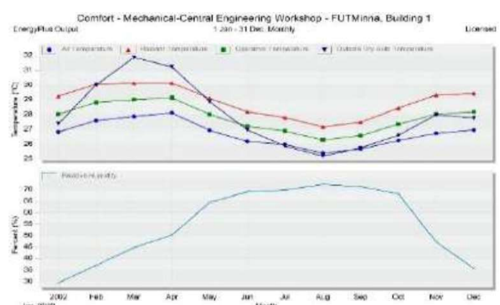

Figure 5: Comfort Data - (Lighting Control)

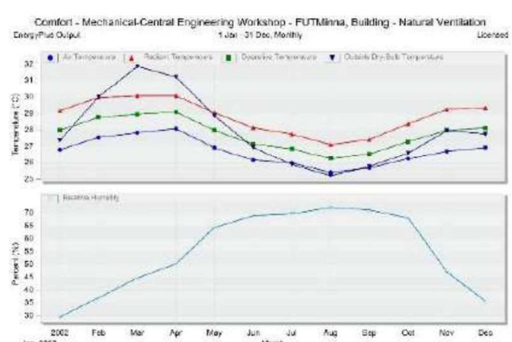

Figure 6: Comfort Data - Mechanical ventilation (Fans)

Figure 7: Comfort Data – (Fan + cooling)

Figure 4-7 presents baseline and various strategies for environmental comfort data simulated such as air temperature registered, radiant temperature reached, operative temperature and relative humidity throughout the year. It is generally observed that maximum temperatures are relatively between the month of March and April.

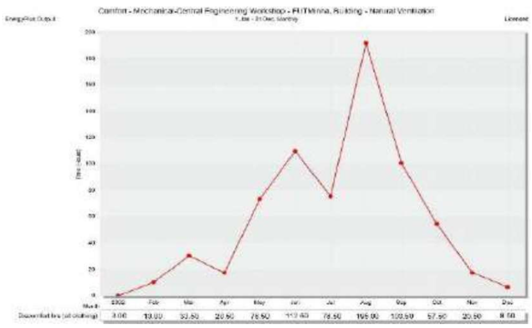

Figure 8: Discomfort hours (Baseline model)

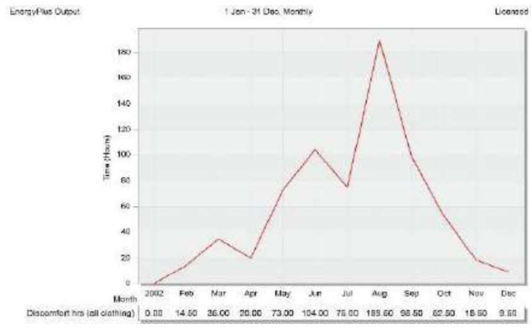

Figure 9: Discomfort hours (Lighting control)

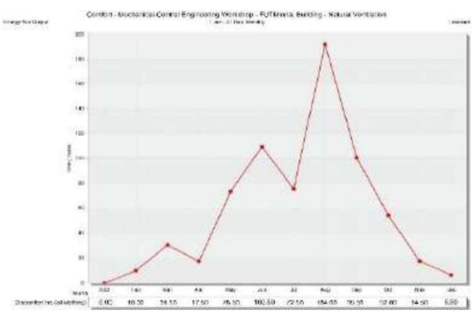

Figure 10: Discomfort hours Mechanical ventilation (Fans)

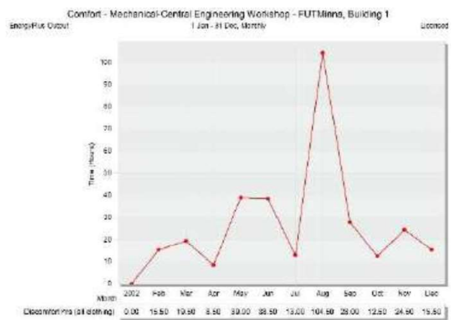

Figure 11: Discomfort hours (Fan + Cooling)

Figure 8, shows that occupants experienced discomfort for 722 hours throughout the year for the baseline model. This is 30.74% discomfort against 69.26% comfort hours out of the total simulation period.

In Figure 9, it can be seen that occupants experienced a total of 690 hours of discomfort throughout the year. This is 29.37% discomfort against 70.63.40% comfort hours out of the total simulation period and hence reductions in the baseline model discomfort by 1.37%. This reduction is attributed to reduced internal gains due to when lighting control is used in the building.

Figure 10, displays that occupants experienced discomfort for 662.5 hours throughout the year. This is 28.20% discomfort against 71.8% comfort hours out of the total simulation period, there is a reduction in the baseline model discomfort by 1.17%.

Figure 11, presents discomfort hours, occupants experienced discomfort for 319 hours throughout the year. This is 13.58% discomfort against 86.42% comfort hours out of the total simulation period, which represents a significant reduction in the baseline model discomfort by 14.62%. This reduction is totally attributed to the scheduled introduction of cooled air into the building.

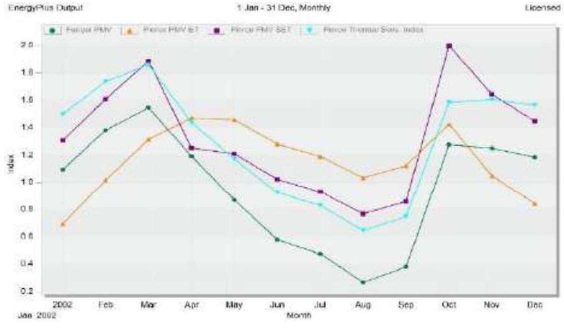

Figure 12: Predicted thermal comfort sensation votes (Baseline model)

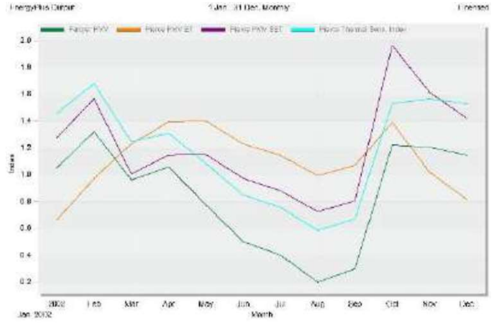

Figure 13: Predicted thermal comfort sensation votes (Lighting control)

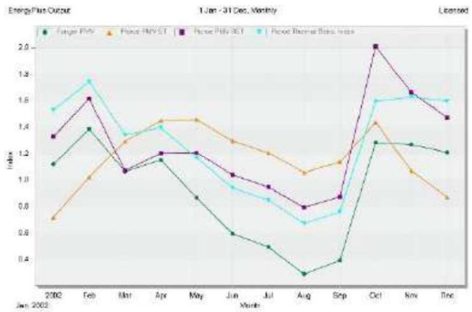

Figure 14: Predicted thermal comfort sensation votes Mechanical ventilation (Fan)

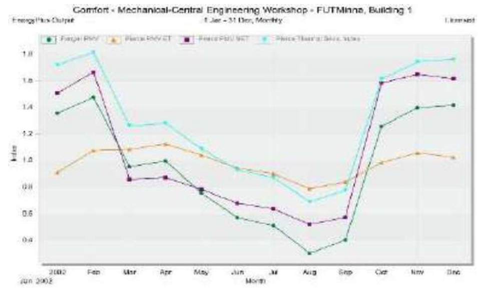

Figure 15: Predicted thermal comfort sensation votes (Mechanical ventilation & Cooling)

Figure 12, presents the predicted thermal comfort sensation index based on Fanger PMV, Pierce PMV ET, Pierce PMV SET and Pierce Thermal Sensation thermal comfort predictive models. The Fanger PMV model predicts thermal comfort close to neutral while the Pierce PMV SET model predicts the worst scenario of all models. It's observed that predicted thermal comfort sensation is slightly improved on application of lighting control, Figure 13, presents predicted thermal comfort sensation votes based on Fanger PMV, Pierce PMV ET, Pierce PMV SET and Pierce thermal sensation predictive model. Figure 14 shows that predicted thermal comfort sensation is majorly from hot to slightly warm on the application of mechanical ventilation. While Figure 15, presents predicted thermal comfort sensation results. It is observed that occupancy thermal sensation votes significantly reduced on application of mechanical ventilation with cooling. Based on the seven points thermal comfort scale, it's observed that the predicted votes placed the comfort sensation majorly between slightly warm and slightly cool for the entire year.

5. CONCLUSION

This study on natural ventilation: applied to engineering central workshop, Federal University of Technology Minna, Niger State, successfully achieved its objectives:

(i) The pattern of natural ventilation in the workshop, through the assessment of various components and external environment, a comprehensive understanding of the workshop's existing conditions and its surroundings was obtained. This provided valuable insights into the baseline ventilation patterns and identified areas for potential improvement. DesignBuilder and EnergyPlus software were used to model the building and perform simulations based on the ASHRAE 55-2004 method. The baseline model predicted thermal comfort votes between "hot" and "slightly warm," with occupants experiencing 30.74% discomfort hours and 69.26% comfort hours throughout the year.

(ii) Better redesigned ventilation pattern were obtained through implementing a lighting control strategy resulted in a slight improvement, shifting the predicted thermal sensation to between "hot" and "neutral." However, the improvement in comfort hours was (1.37%). Similarly, mechanical ventilation with fans showed minimal improvement (1.17%), leaving the predicted thermal sensation between "hot" and "slightly warm." Significant improvement was achieved with mechanical ventilation and scheduled cooling, which placed the predicted thermal sensation between "slightly warm" and "slightly cool," with the majority of occupants experiencing "neutral" conditions. This strategy increased comfort hours by 14.62% compared to the baseline.

(iii) By evaluating and comparing the results with the original workshop design. The study assessed the efficiency and effectiveness of the existing ventilation system. This analysis served as a reference point for evaluating the performance of the redesigned ventilation pattern. These findings highlight the potential of mechanical ventilation and scheduled cooling to improve thermal comfort in naturally ventilated buildings in hot and humid climates like Minna, Niger State. While lighting control and mechanical ventilation with fans offered minimal benefits, the combination of mechanical ventilation and scheduled cooling significantly enhanced occupant comfort.

The following recommendations were proposed:

i. Implement the redesigned ventilation pattern: The study highlights the benefits of the redesigned ventilation pattern in terms of improved airflow, thermal comfort, and energy efficiency. It is recommended to implement the proposed design changes in the Engineering Central Workshop to enhance the indoor environment and reduce energy consumption.

ii. Regular maintenance and monitoring: To ensure the continued effectiveness of the natural ventilation system, regular maintenance and monitoring are essential. This includes cleaning and maintaining ventilation openings, inspecting airflow paths, and periodically evaluating indoor air quality and thermal comfort.

iii. Further research and validation: While this study provides valuable insights, further research and validation are recommended for conducting on-site measurements and comparing them with simulation results can help validate the accuracy of the models and provide more robust conclusions.

Overall, this parametric study on natural ventilation in the Engineering Central Workshop contributes to knowledge by providing a detailed understanding of the existing ventilation patterns, proposing a better ventilation design, evaluating its performance, and offering practical recommendations for enhancing natural ventilation in workshop environments.

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