
A COMPUTATIONAL INVESTIGATION OF WINDOW GEOMETRY'S IMPACT ON THERMAL COMFORT IN MULTI-STOREY BUILDINGS

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Abstract

Incorrect sizing of the windows has a significant effect on the thermal comfort of the occupants in a naturally ventilated building. This study attempts to numerically investigate the effect of window geometry in terms of window-to-wall ratio (WWR) on thermal comfort of a naturally ventilated storey building. A three-storey hypothetical model was developed using DesignBuilder software. Predictive Mean Vote (PMV) of each of the floor was numerically determined using DesignBuilder CFD simulation. The effects of the WWR on the thermal comfort in each of the floor were parametrically determined by varying the WWR from 10% to 50% step of 5%. The numerical results show that the thermal comfort was achieved when the WWR range from 20% to 30%, 15% to 25%, and 10% to 25% for the ground floor, first floor, and the second floor respectively. However, the WWR that gave better results for the ground, first, and the second floors were 25%, 20% and 15% respectively because their respective PMV values were closer to the thermal neutrality. Building engineers and designers could find this information helpful during building design decision making.

Keywords: Storey building, window-to-wall ratio, thermal comfort, Predictive Mean Vote

INTRODUCTION

Building envelope plays a significant role in creating a comfortable living environment. More often than not, people spend about 25% of their daily time in indoor environment, especially in civil service. Therefore, the morale, productivity, efficiency, concentration, and well-being of building occupants are largely dependent of their indoor environment (Kim *et al.*, 2016; Ravat *et al.*, 2017; Sun *et al.*, 2018). Thermal comfort and indoor air quality (IAQ) are the most important indoor environments and hence, achieving thermal comfort in a building envelope is essential for enhanced occupant's performance (Urge-Vorsatz *et al.*, 2015).

Thermal comfort is the state of mind that expresses satisfaction with the thermal environment and hence, the provision of thermal comfort to the user of a building is crucial. A building is said to be comfortable if 80% of its occupants are thermally comfortable (Koranteng *et al.*, 2015).

In building thermal analysis, window is considered a special kind of component that has a total heat transfer coefficient of about five times of other components of the building such as the walls, roof, etc. (Lee *et al.*, 2012; Sun *et al.*, 2018). According to Sun *et al.* (2018), window accounts for about 60% of the total energy consumption of a building envelope. Designers of modern buildings use large area of windows for aesthetic requirements and optical comfort (Kiet Lau *et al.*, 2016). The cooling load of a building tend to increase as a result of an increase in the window area. This increase in the window area consequently affects the thermal comfort of the occupants in the occupied space (Kiet Lau *et al.*, 2016; Al-Masrani *et al.*, 2018). The window area often expressed in terms of window-to-wall area ratio (WWR) plays a crucial role in building energy consumption for cooling, heating, and thermal comfort (Yemo *et al.*, 2020).

Numerous studies have been conducted to examine the effect of geometry of windows on the thermal comfort and air quality of a naturally ventilated occupied space. The optimization of window opening design for thermal comfort in a free-running building was conducted by (Stavarakakis *et al.*, 2011). Rudraprasad and Sandhyata (2014) studied the effects of window geometry and location on natural ventilation and thermal comfort in a residential building situated in hot and humid climate. Koranteng *et al.* (2015) investigated the effects of window geometry and position on indoor comfort for residential building in Kumasi, Ghana using parametric simulation. Prakash and Ravikumar (2015) investigated the thermal comfort and airflow characteristics of a residential building with adjacent window openings under a generalized position of window openings. Despite many studies conducted to investigate the effect of window geometry and position in free-running buildings, a research is missing in the investigation of the effect of window geometry of the floors of a naturally ventilated storey building on the thermal comfort of the occupants. Therefore, this study is targeted at numerical investigation of the effect of window geometry in terms of WWR on the thermal comfort of the occupants of a naturally ventilated 3-storey building.

Predictive Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are the two thermal comfort indices in the Fanger's model. The PMV Index predicts the thermal comfort of a building based on the 7-point ASHRAE scale of thermal sensation ranging from -3 to +3, with the zero point being thermal neutrality (ASHRAE-55, 2010).

On the ASHRAE scale of thermal sensation, the range of the PMV values from -0.5 to +0.5 represents the state at which the building occupants are thermally comfortable. For this study, the influence of WWR on the thermal comfort of the storey building is examined numerically using the PMV index.

STUDY BUILDING

The study building was a hypothetical 3-storey office building situated in the new Campus of Bayero University Kano. The building is free-running with two opposite windows on each floor. The hypothetical building is shown in Figure 1.

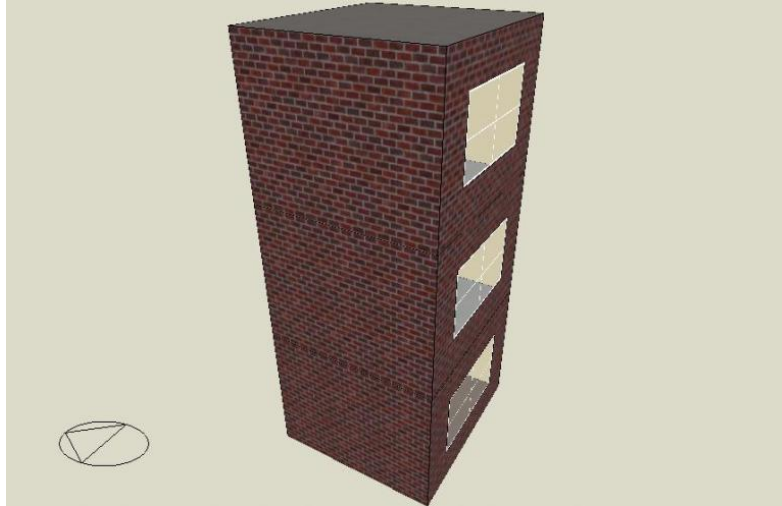


Figure 1: Hypothetical 3-storey building

METHODOLOGY

In order to numerically investigate the effect of the WWR on a naturally ventilated 3-storey office building, the following methods highlighted below were logically followed.

Numerical Study

The numerical study was carried out in two stages: (1) External CFD analysis of airflow through the window openings of each floor under natural ventilation settings. (2) Internal CFD analysis for numerical determination of the thermal comfort PMV inside the offices at a height of 1.1 m above the floor level using DesignBuilder software.

Creation of the hypothetical model of the 3-storey office building

The hypothetical model of the 3-storey office building was created using DesignBuilder software. On each of the floors, an office of dimensioned 4m by 3.7m by 3m was created. The doors are considered adiabatic walls. On each of the floors, the block and the zone levels are shown in Figure 2(a) and (b) respectively. The computational domain of the storey building is shown in Figure 3.

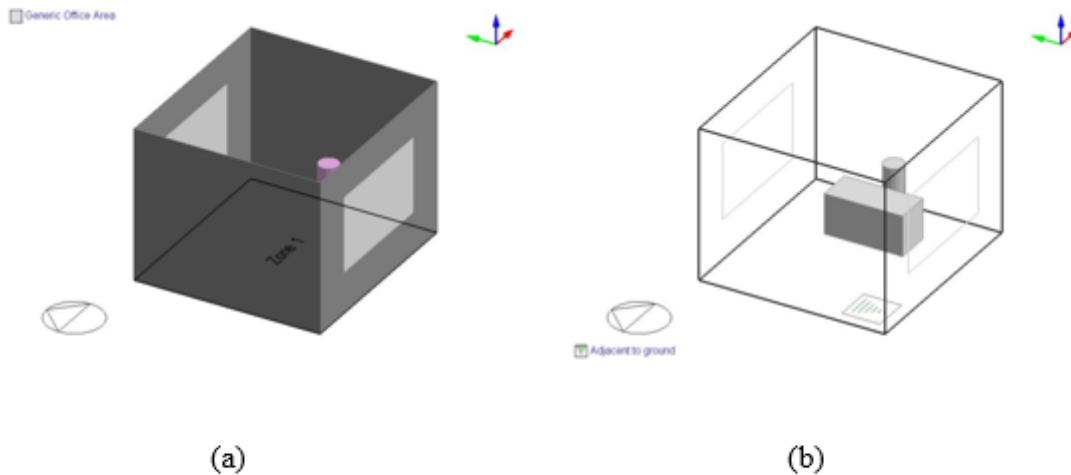


Figure 2: Block and zone levels of each office

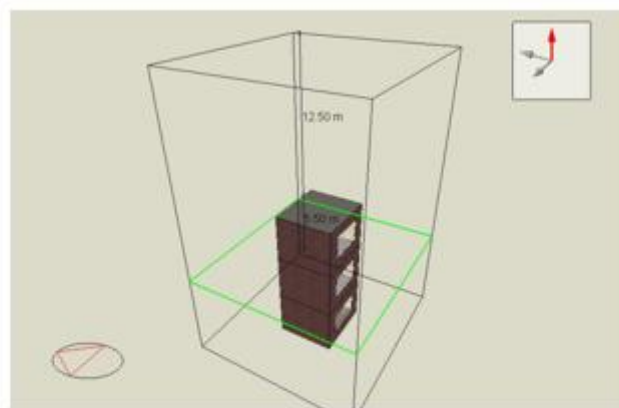


Figure 3: Computational domain of the storey building

Mesh generation and sensitivity analysis

Mesh independence test and sensitivity analysis were carried out on the office zone on each floor. Mesh generation and independence test with a good computational mesh are essential for a successful and accurate solution (Rahmati *et al.*, 2018). The resulting solution would be inaccurate if the mesh is too coarse and on the other hand, the resulting solution would be accurate but the computation time and cost would be prohibitive if the mesh is too fine (Rahmati *et al.*, 2018). In essence, solution cost and accuracy are functions of power quality. Uniform rectilinear coordinate meshes were used to generate the building model's mesh.

A mesh was generated using default parameters for a coarse mesh containing the minimum number of elements required to represent the geometry of the single zone model and satisfy the default mesh rules. As shown in Figure 4(a), the default mesh spacing of 0.300, gridline merge tolerance of 0.0300, and 42147 elements were used for each of the offices. To ensure mesh independence, three more refined meshes with 205917, 487,983 and 634,256 elements were generated for the offices on the ground, first and second floors by using the "Max. X size", "Max. Y Size" and "Max. Z Size". These refined meshes are shown in Figure 4(b, c and d).

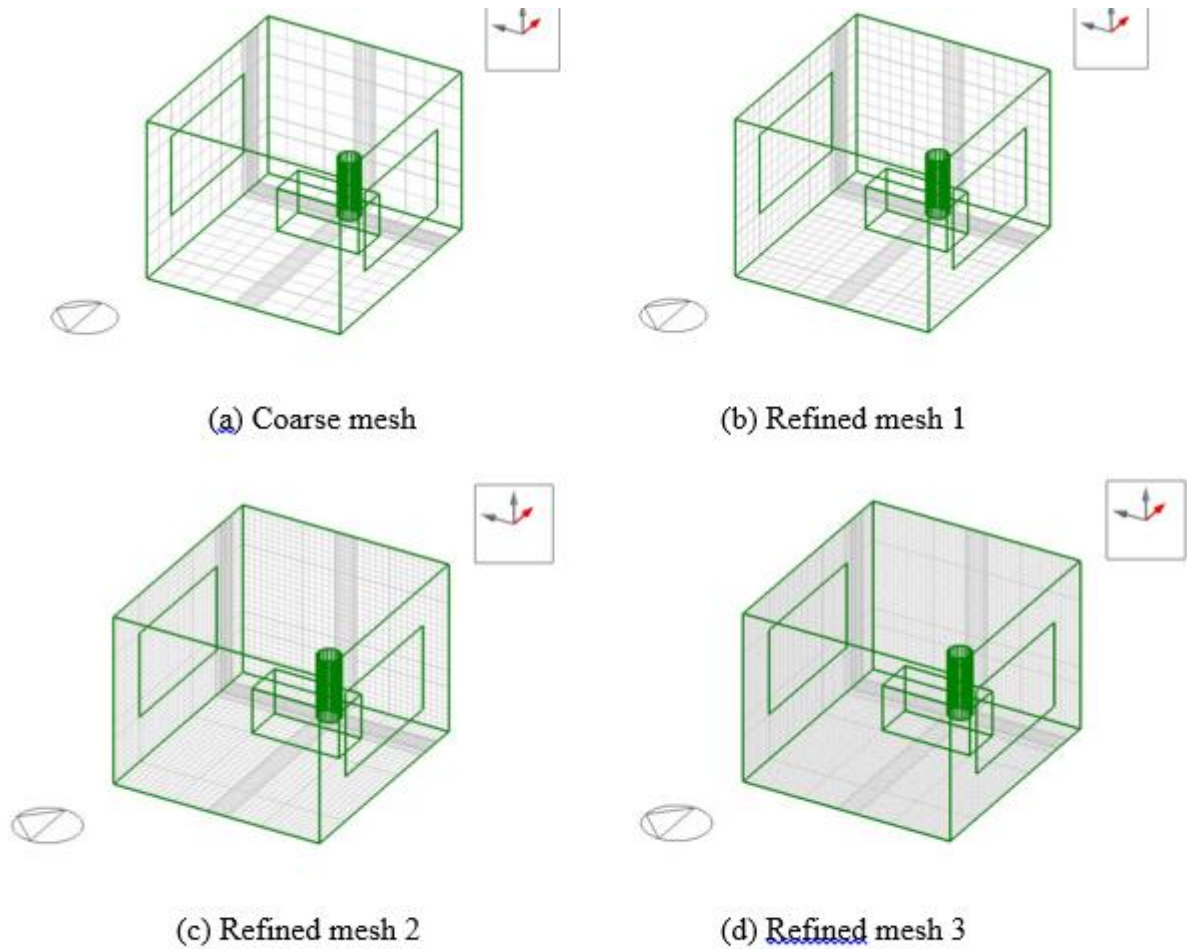


Figure 4: Coarse and refined mesh of the geometrical model

In each mesh (coarse and fine), the temperature distribution was measured at a height of 1.1 m above the floor, which corresponds to the shoulder of a seated occupant, as recommended by ASHRAE Standard-55, 2010. The coarse mesh with 42147 elements differs from the finest mesh with 634,256 elements by about 15%, while the refined mesh 1 and 2 differ from the finest mesh by 3.2% and 1.3%, respectively. Therefore, the refined mesh 2 with 205917 elements was considered sufficient for the purposes of the numerical simulation.

Assigning the boundary conditions

In this study, the boundary conditions employed for the CFD analysis are summarized in Table 1.

Table 1. Boundary conditions for internal and external CFD simulations

Internal CFD Analysis		External Analysis	
South window	Airflow rate: 83 l/s Temperature: 26.2°C		Grid spacing (m): 2.0000 Grid line merge Tolerance (m): 0.2000 Velocity (m/s): 3.44
Eastern wall	Fixed heat flux: 0.382 kW	Wind analysis	Direction : South
Southern wall	Fixed heat flux: 0.238 kW		
Other walls, ceiling and floor	Isenthalpic		
Occupants	One occupant, fixed heat flux: 8.11W/m ²		Exposure: Suburban
Equipment	12 laptops, fixed heat flux: 3.37 W/m ²	Site domain factors	Length (m): 3.00
Metabolic rate	1.0 met (58.2 W/m ²)		Width (m): 3.00
Clothing level	0.5 clo (0.08 °C. m ² /W)		Height (m); 1.40
Zone air temperature	30.5°C		
Zone relative humidity	60%		
Number of sphere segments in mean radiant temperature calculation	24		

The governing equations

The numerical method employed is known as a primitive variable method, which involves the solution of a set of equations that describe the conservation of heat, mass, and momentum. The equation of mass conservation, known as the continuity equation, is given by equation 1 (Phonekeo *et al.*, 2016).

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

The equation for momentum conservation is given in equation 2.

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \quad (2)$$

The equation for total energy conservation is given in equation 3.

$$\frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) + u_i \frac{\partial P}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_j} \quad (3)$$

Where: ρ = Density; u_i = Velocity component in the i direction; P = Static pressure; τ_{ij} = Stress tensor; x_i = Cartesian coordinate; g_i = Gravitational acceleration in the i – direction; h = Static enthalpy; k = Thermal conductivity; T = Temperature.

The CFD numerical method which relates to the set of those equations above, particularly describes the main environmental factors, including the conservation of heat, temperature, mass, momentum, and where a turbulence model is used. The equations comprise a set of coupled non-linear second-order partial differential equations having the following general form, in which the dependent variable is given by equation 4.

$$\frac{\partial}{\partial t}(\rho \phi) + \text{div}(\rho u \phi) = \text{div}(\tau \text{grad} \phi) + S \quad (4)$$

The rate of change and convection are represented by the first and second terms on the left, respectively, while the diffusion and source terms are represented by the first and second terms on the right, respectively. The turbulence model is regarded as critical in numerical modeling for describing the flow behavior of the indoor thermal environment (Parra *et al.*, 2006). Therefore, in this study, the standard k-e turbulence model was used since it is a well-

established method in research on natural ventilation (Hughes *et al.*, 2012). The Upwind scheme was also employed for the discretization of the transport equations.

Determination of airflow through the windows

External CFD analysis was carried out to determine the velocity of airflow through the windows of the ground, first and the second floor. The 3D contour plot showing the CFD external airflow around and into the building is shown in Figure 5.

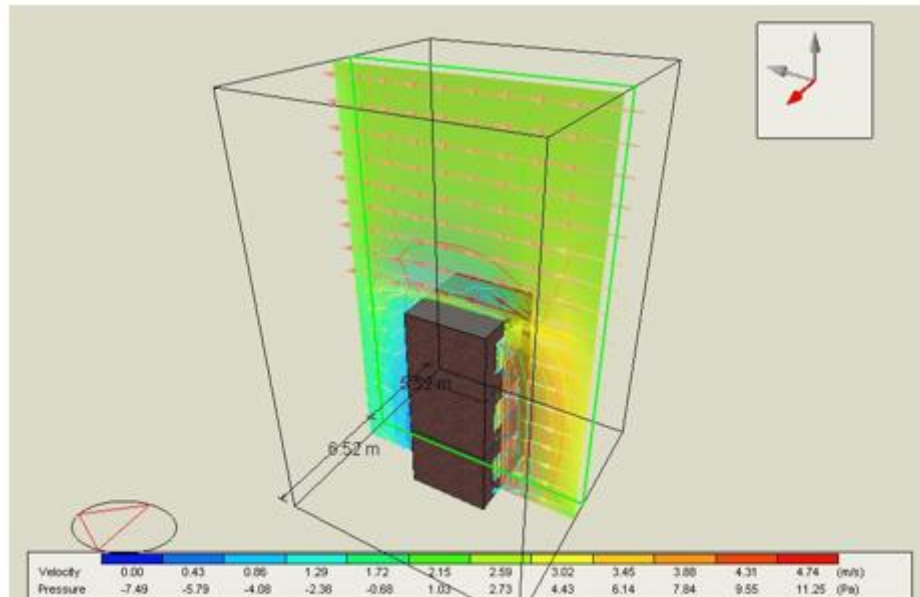


Figure 5: External CFD analyses of the airflow around the storey building

Model validation

After the mesh independence study, the accuracy of the model was determined through a validation process. The model was validated by comparing the simulated PMV values with the values obtained using the Centre of Built Environment (CBE) thermal comfort tool (Figure 6).

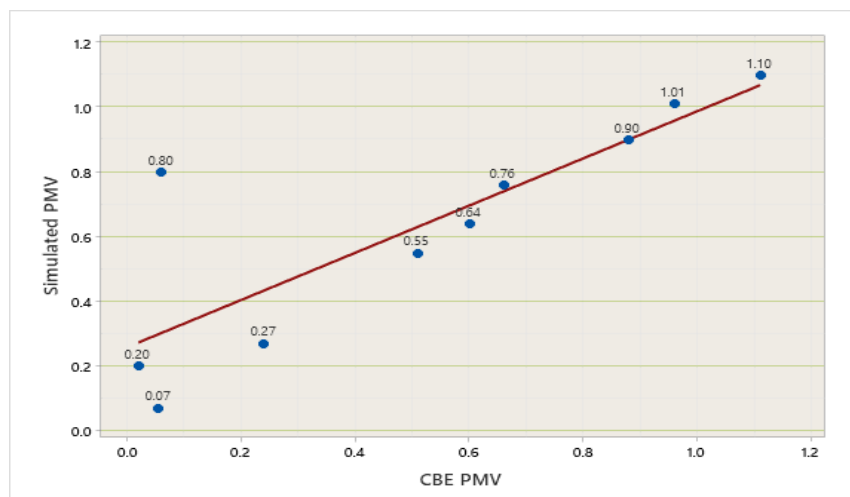


Figure 6: Comparison between CBE and simulated indoor temperature

The coefficient of correlation between the simulated PMV and the values of PMV obtained from the CBE tool at a 95% confidence level using Minitab 20 software was 0.831. The high correlation indicates the high accuracy of the building model used for the study.

Determination of Thermal Comfort of the Building Model

The indoor parameters such as the temperature, relative humidity, air velocity, clothing insulation of occupants, and the metabolic rate of the occupants were used as input for the CFD simulation for the determination of the PMV Fanger's thermal comfort index.

Parametric Analysis of the CFD Model

For each of the floor, parametric analysis was employed by keeping the boundary conditions constant while varying the WWR from 10% to 50%, step 5%. DesignBuilder CFD simulation was then carried out to determine the optimum WWR for each of the floors using the thermal comfort PMV index as the optimization objective function.

RESULTS AND DISCUSSION

The window geometry in a naturally ventilated building determines how comfortable the occupants of a space would be. The 3D contour plots of the PMV of the study storey building with representative WWR of 10% and 30% for the ground floor, first floor, and second floor are shown in Figures 7, 8 and 9 respectively.

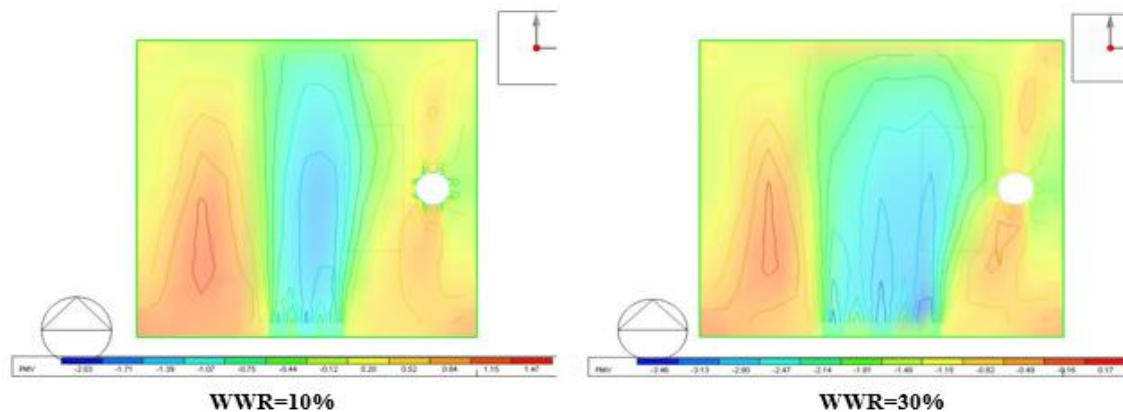


Figure 7: PMV contour plot of ground floor office

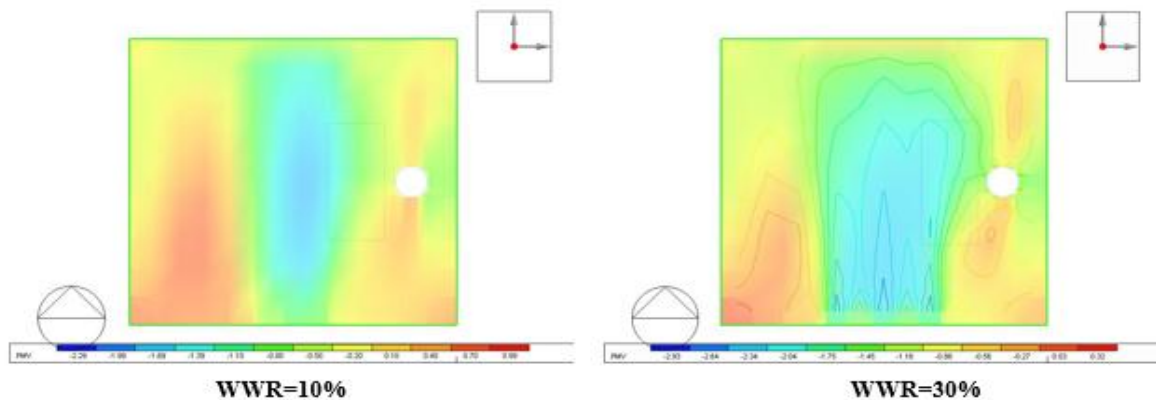


Figure 8: PMV contour plot of first floor office

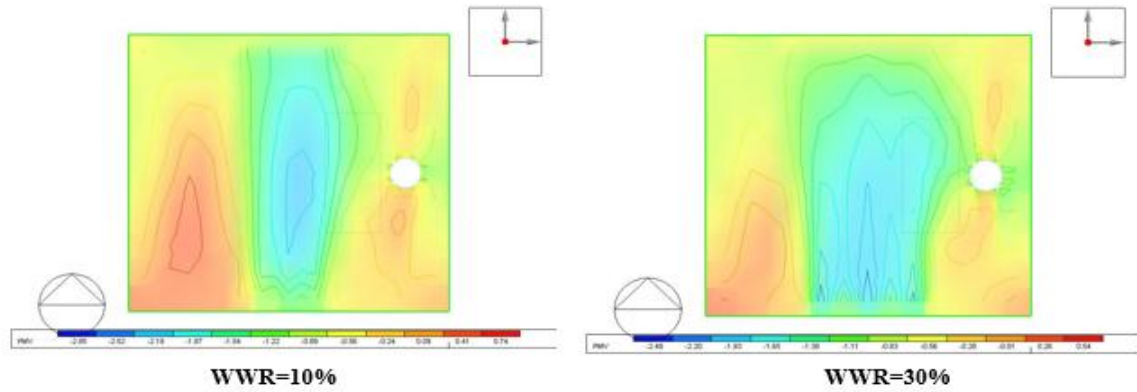


Figure 9: PMV contour plot of second floor office

The parametric simulated values of the ground floor, first floor and second floor represented by PMV_g, PMV_f, and PMV_s respectively of the study storey building with WWR of 10% to 50% step 5% are shown in Fig. 10.

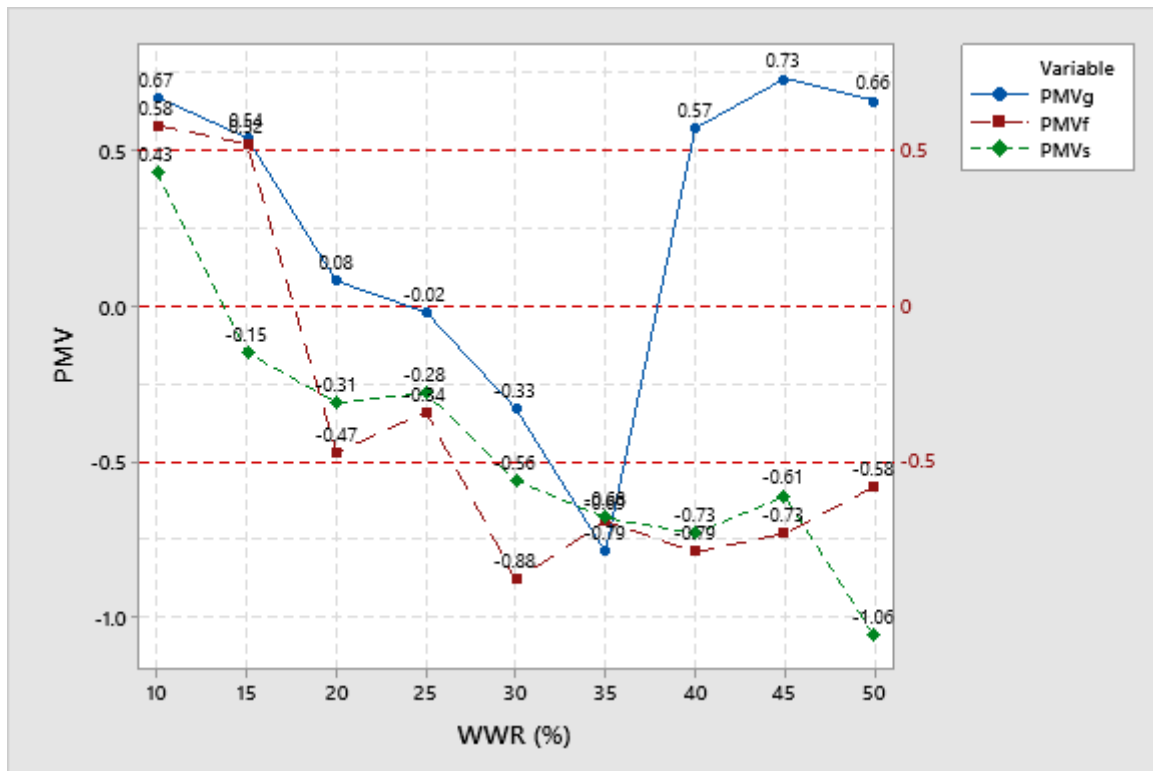


Figure 10: Plot of PMV vs WWR(%)

The results of the selected 3D contour plots of the parametric simulations of the hypothetical storey building with WWR of 10%, 20%, 30%, 40%, and 50% are shown in Figure 7-9 while for the PMV values with WWR of 10% to 50% step of 5% are shown in Figure 10. Based on ASHRAE Standard-55 (2010) recommendations, it can be seen that the values of PMV when the WWR were 20%, 25% and 30% fall within the thermal comfort band of -0.5 to +0.5 for the ground floor. For the first floor, the WWR of 15%, 20% and 25% have PMV values that fall within the thermal comfort band while for the second floor, WWR of 10%, 15%, 20% and 25% have PMV values that fall within the thermal comfort band. This implies that the

height of a building floor above the ground level has a significant effect on the window geometry from thermal comfort standpoint. This might be attributed to the fact that in a naturally ventilated building, the higher the floor level above the ground the more the building is naturally ventilated because of the less obstacles that impede air flow through the window.

This study also showed that upper floors of naturally ventilated storey building may use relatively smaller WWR and still achieve thermal comfort. Hence, to achieve thermal comfort in the hypothetical naturally ventilated storey building under study, the WWR for the ground floor to be used should range from 20% - 30%, for the first floor, the WWR should range from 15% to 25% while for the second floor, the WWR should range from 10% to 25%. Nevertheless, the best results were obtained when the WWR were 25%, 20% and 15% for the ground, first, and the second floors respectively because their respective PMV values were closer to the thermal neutrality. These findings agreed with the reported work of Koranteng *et al.* (2015) who stated that a WWR of 10%-40% for naturally ventilated buildings gives an enhanced thermal comfort. Shaeri *et al.* (2019) and Lee *et al.* (2012) in separate studies agreed with this finding who highlighted that in free-running buildings enhanced thermal comfort and energy consumption is achieved when the WWR ranges from 10%-30%.

CONCLUSION

The influence of the window geometry in terms of WWR on the thermal comfort of occupants of a hypothetical naturally ventilated storey building was numerically investigated. The WWR that gave better results for the ground, first, and the second floors were 25%, 20% and 15% respectively because their respective PMV values were closer to the thermal neutrality. The WWR of each floor of a naturally ventilated storey building needs to be optimized using thermal comfort as the objective function. This study could help building designers and engineers to size windows of naturally ventilated building.

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