PREDICTIVE MEAN VOTE (PMV) ASSOCIATED WITH USE OF ALTERNATIVE WINDOW TYPES IN ZARIA, NIGERIA

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ABSTRACT

The fact that windows contribute to the achievement of thermal comfort in various climatic conditions is clearly understood. However, there is the need for a better understanding of the relationship between window types and thermal comfort in order to optimize their use. This will result in the downsizing of mechanical systems, which is central to the pursuit of sustainable built environment. It is in this light that this paper examines the relationship between window types and PMV in buildings, with reference to the climatic conditions in Zaria, Nigeria. Autodesk Simulation Computational Fluid Dynamic (CFD) software was used to compare alternative window types using the comfort limits set by the ASHRAE Standard 55-2004 and ISO Standard 7730. The result shows that the PMV in spaces in Zaria will vary based on the window type used. This variation directly affects the PPD with the thermal comfort conditions within the space. Also, louvered and casement windows resulted in better thermal comfort. It is therefore recommended that casement windows and louver windows be used in buildings in Zaria since they can be opened when ventilation is required for thermal comfort and closed is cooler periods when much airflow is not required.

Keywords: Computational Fluid Dynamics, Percentage of Persons Dissatisfied, Predictive Mean Vote, thermal comfort, ventilation, window.

INTRODUCTION

Thermal comfort is a component of Indoor Environment Quality (IEQ), and a major concern in the quest for sustainable built environment. This is very important considering the enormous energy challenges faced by many countries, and the amount of Green House Gas (GHG) emissions associated with energy generation. Sun, Luh, Jia, Jiang, Wang, and Song (2013) noted that the energy consumed in buildings accounts for 40% of the total energy consumed in the entire world, and air conditioning systems are responsible for 40%–50% of this energy. This makes the reduction of the need for air conditioning systems in buildings is a priority in building design. Rajapaksha and Hyde (2005) highlighted the two dimensions of operational energy minimization in buildings. These are; the reduction of energy demand, and, the supply of energy through renewable means. Reduction of energy demand lies in a return to the basic passive design strategies that rely on the natural characteristics of their locations, thereby downsizing mechanical systems. In this context, natural ventilation has established itself as an attractive and viable alternative in the design of the building envelopes. This can be achieved simply through direct supply of external air through the windows. (AA Environment and Energy Performance, 2015).

The requirement for natural ventilation in buildings cannot be satisfied simply by providing openable windows, but by understanding how the window types and configurations influence the quality of ventilation (Caifeng, 2011a). In contrary to this, many architects in Nigeria appear to emphasize the aesthetic dimension of windows as a component of the building façade, at the expense of ventilation. Huizenga, Zhang, Mattelaer, Yu, Arens and Lyons (2006) highlighted the importance of windows to thermal comfort, and subsequent reduction of building energy consumption, and noted that a better understanding of how they affect comfort might lead to even greater savings.

Kim, Min, and Kim (2013) identified the theory of predicted mean vote (PMV) developed by Fanger (1970) as the most representative thermal comfort model. PMV is an index that represents the predicted mean vote (on the thermal sensation scale) of a large population exposed to a given environment, and is acknowledged as an international thermal environment indicator. It is in this light that this paper examines the relationship between window types and PMV in buildings, with reference to the climatic conditions in Zaria, Nigeria. The objectives are to:

i. Determine the Predictive Mean Vote (PMV) in spaces with alternative window types.
ii. Determine the Percentage of Persons Dissatisfied (PPD) with thermal condition in the spaces.
iii. Compare the PMV and PPD associated with the window types.

LITERATURE REVIEW

The literature review focuses on two issues. The first is the theory of predictive mean vote as a measure of thermal comfort, while the second looks at the association between windows and PVM.

Predictive Mean Vote (PVM) and Thermal Comfort

Kumar, Singh, and Sud (2009) noted that it was not possible to create a condition within which everyone was comfortable as reflected in ISO 7730, which considers 80% of occupants as a reasonable limit for the number of people who should be thermally comfortable in an environment. Several methods are used for the estimation of thermal sensation and comfort. Holopainen (2012) noted that the International Standards Organisation ISO 7730 (2005) and ASHRAE 55 (2004) used Fanger's PMV method. The PMV is a thermal comfort index used for measuring comfort levels inside a conditioned space. This is based on the effect of temperatures that deviate from that required for optimal comfort on inhabitants of a space, and can be predicted by determining the Percentage of Persons Dissatisfied (PPD). Kim, Min, and Kim (2013) identified the theory of PMV as the most representative thermal comfort model. The PMV is an index that represents the predicted mean vote on the thermal sensation scale, for a large population exposed to a given environment, and is acknowledged as an international thermal environment indicator (Lee, Cho, Yun, & Lee, 1998). This method is based on ASHRAE thermal sensation scale (ASHRAE 1993). It involves a seven-point thermal sensation scale ranging from -3 to +3, where -3 stands for cold condition, zero stands for neutral and 3 stands for hot conditions (Table 1). Large number of individuals were expected to cast their vote on the scale and this was used to determine the PMV which is an index that predicts the mean value of the votes. This means that thermal comfort was not measured by air temperature but by the number of people complaining of thermal discomfort as noted by Kumar, Singh, and Sud (2009).

Table 1. ASHRAE thermal sensation scale

Index	Thermal sensation
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cold
-2	Cool
-3	Cold

Source: ASHRAE (1993)

Predictive Mean Vote and Windows

Caifeng (2011b) noted that although the same kinds of windows exist in many regions, window specifications such as size, material, climatic conditions/requirement and use in different building types are the basis for the dichotomy in window design.

A number of studies have discussed the strong relationship between window type and ventilation quality. Bouter (1987) noted that there is a strong relationship between the window design and the quality of ventilation, which ultimately influences comfort level and performance of users in a space. The effective ventilation of a space is strongly attributed to effectiveness of the opening area of the window design in utilizing the concept of passive ventilation (Bouter, 1987; Kleiven, 2003). However, Lyons, Arasteh, and Huizenga (2000) noted that there were no specific procedures for predicting the comfort impact of windows, but noted that PMV and PPD along with ASHRAE standards were commonly used. ASHRAE (2005) offers basic guidance about windows and comfort for the designer. Huizenga et al. (2006) noted that windows influenced thermal comfort in three ways. These are through long-wave radiation from the warm or cold interior glass surface, transmitted solar radiation induced air motion (convective drafts) caused by a difference between the glass surface, and temperature and the adjacent air temperature.

Heilsberg and Svidt (2001) suggested that side-hung windows are preferred to top-hung windows in admitting enough air into the indoor spaces. Similarly, Breezway Technical Bulletin (2012) noted that side-hung windows offered almost 90% ventilation area in directional opening and 70% in centre opening, while top-hung windows offer 40%- 70% in ventilation area. Another common window type is the louvered window. This allows 90% ventilation area when opened at 90 degrees to the frame, offering almost its entire window area for air passage. It can also be opened at angles or by degrees to regulate how much air passes through (Breezway Technical Bulletin, 2012). This high ventilation area allows more airflow when compared to what is perhaps the most common window type in Nigeria, the horizontal sliding window. Horizontal sliding window offers a maximum of 40-50% in ventilation area (Breezway Technical Bulletin, 2012).

METHODOLOGY

The study was based on the use of modelling and simulation software. Autodesk Simulation Computational Fluid Dynamics (CFD) was used for the simulation. Simulation CFD harnesses the seamless transmission and translation that exist between modelling software like Revit Architecture and Autodesk Solid works in obtaining building information in 3D model format (Premkumar, 2013). It requires the input of climatic data for the location of the study, and incorporates the ASHRAE Standard 55-2004 and ISO Standard 7730 which defines the range of indoor environment conditions acceptable to a majority of occupants, and used in optimizing airflow in a space (ASHRAE, 2004). The comfort limits set by this standard are:

i. Predicted Mean Vote (PMV), which shows how comfortable a group of occupants in a statutory position are in a space based on the ASHRAE thermal sensation seven-point scale which rates from +3 to -3 (hot - cold), with a neutral value at zero.
ii. Predicted Percentage Dissatisfied (PPD), which is a quantitative prediction of the percentage of people that will be dissatisfied with the thermal conditions, as determined by PMV (Premkumar, 2013). As PMV drifts away from neutral (PMV=0) either negatively or positively, PPD increases. Maximum PPD is100% and a constant minimum of 5% even in relatively comfortable conditions (Abodunrin, 2014).

iii. Velocity must be at or below 0.254m/s within 300mm from the walls and vertically between 1800mm and 150mm.
iv. Difference in temperature between ankle and head positions (for a seated occupant) is 2℃ (3.6 F).
v. The Average air temperature is between 22.77℃ -25℃.
vi. There should be maximum mixing of air in the space (Premkumar, 2013).

Three-Dimensional (3D) Modelling

Three Dimensional (3D) models were produced with the use of Revit Architecture software. These models were of minimal geometrical detail in order to reduce simulation time. The rooms were of 9.9m^2 floor are (3.3mx3.0m), and 2.7m headroom. The room size was based on average room size in Zaria (Kawu, Ahmed, & Usman, 2012). Four window types were used in the models. These are; top-hung; louvered, horizontal sliding, and casement windows. The windows were 1200mm x 1200mm in dimension. Material specification of the geometry were stated concisely to aid easy identification by Simulation CFD as shown in Table 2. Also, climatic data was used to create boundary conditions which serve environmental conditions for the simulation as shown in Table 3.

Table 2 Material conditions used in the CFD Simulation

3D Model Geometry Type (geometry classification based on Revit material)	**CFD Simulation Materials**
External walls (sandcrete)	Concrete
Window ventilation area	Air inlet
Window pane glass	Glass
Furniture	Particle board
Seated occupant	Human
Ceiling	Wood (soft)
Floor	Concrete
Internal Volume	Air (Variant)

Table 3 Boundary conditions for this simulation.

Climatic Data	**Boundary conditions**
Average mean temperature (25.93˚C)	Temperature coefficient/Boundary (25.93˚C)
Average Wind speed (1.63 m/s) for air inlet	Volume flow rate (for opening area) =2.3472m3/s
Human boundary conditions	Total heat generated condition for a stationary person in a seating position 58.2W/m^2 /1 met/60˚ (ASHRAE, 2014)
Air outlet	Zero-gauge Pressure

RESULT AND DISCUSSION

The result of the study is presented and discussed under seven headings. These are; Predicted Mean Value (PMV), Percentage of Person Dissatisfied (PPD), difference in temperature between ankle and head positions, average air temperature, air velocity, mixing of air, and comparison between window types.

Predicted Mean Vote (PMV)

The result of the study shows the PMV values for the casement window in Zaria ranges from -1.69 to +3 indicating that the lower body would be in the slightly warm to hot range and the upper body in the slightly warm to neutral range. For the sliding window, the PMV range falls between -1.49 to +3. This shows that the lower body would fall within the slightly warm to hot range, while the upper body would fall within the slightly warm to neutral range.

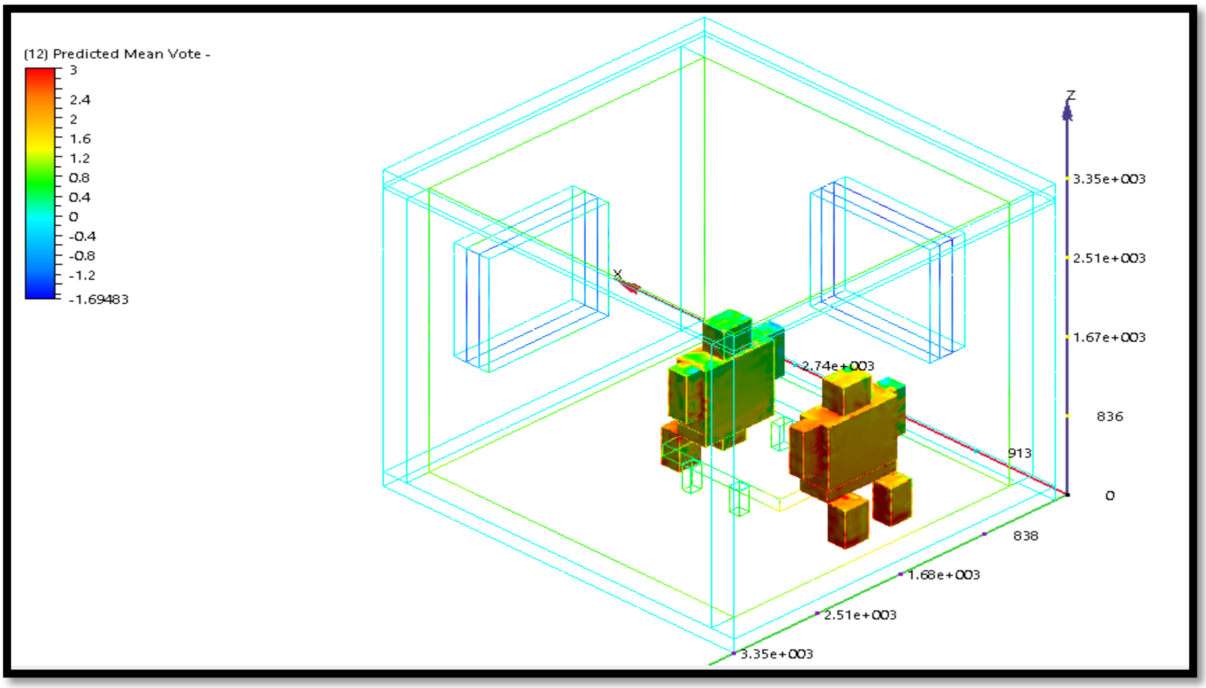

Figure 1. PMV scale for casement window in Zaria

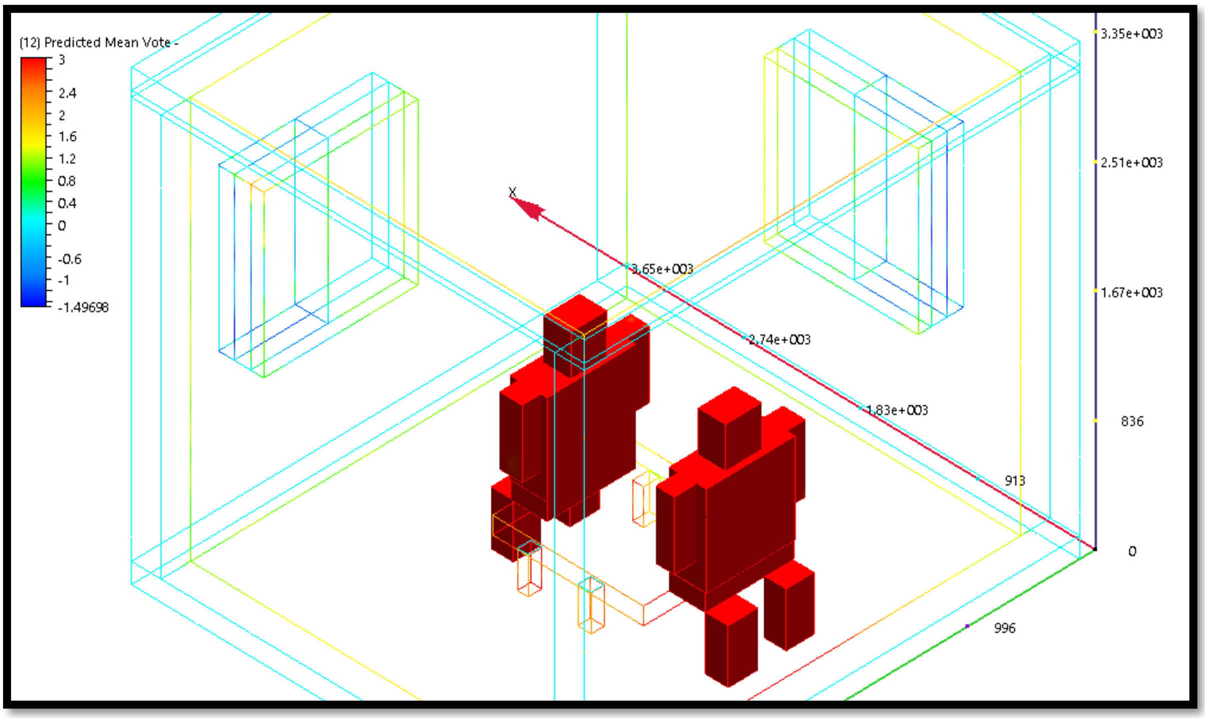

Figure 2 PMV scale for occupants in the sample space with the sliding window

For the awning or Top hung the PMV range falls between -1.782 to +3. This indicates that the majority of the lower body falls within the warm to hot range, while the upper body falls within the slightly warm and warm. PMV result for the louvres indicate a range of -1.45 to +3 with the lower body ranging from slightly warm to hot range while the upper body in the slightly warm to neutral range (Figure 1 to 4).

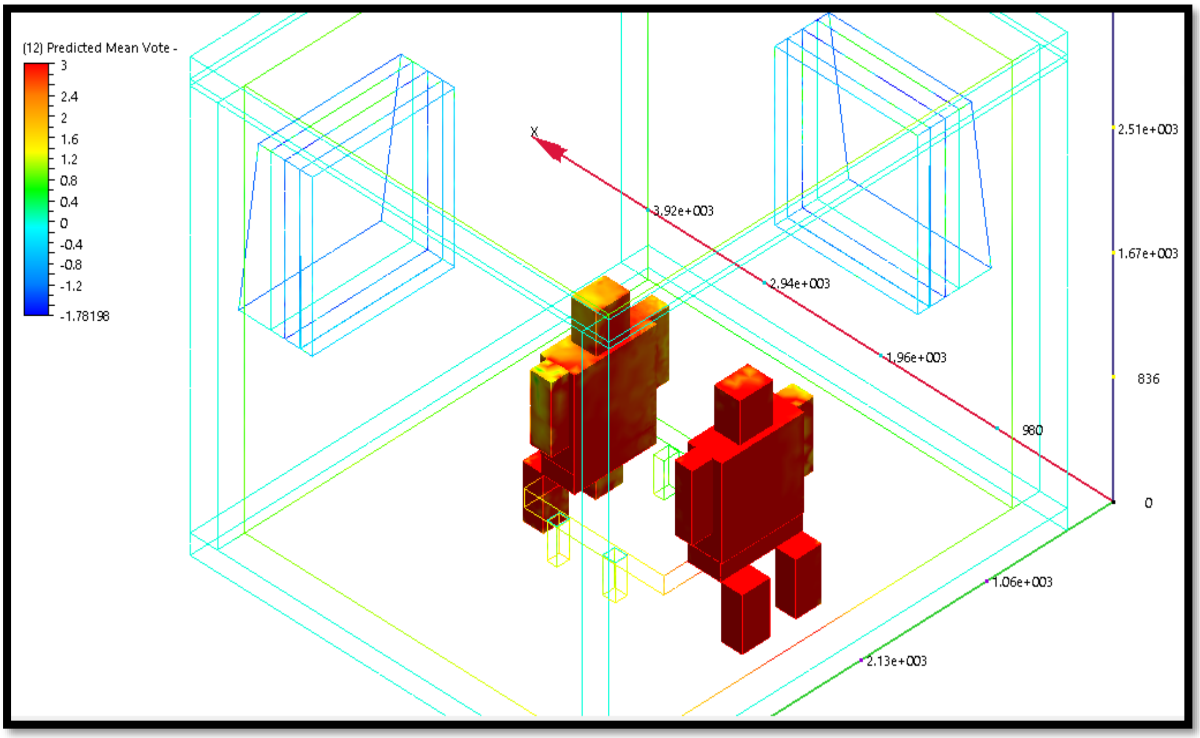

Figure 3. PMV scale for Top hung /Awning Window

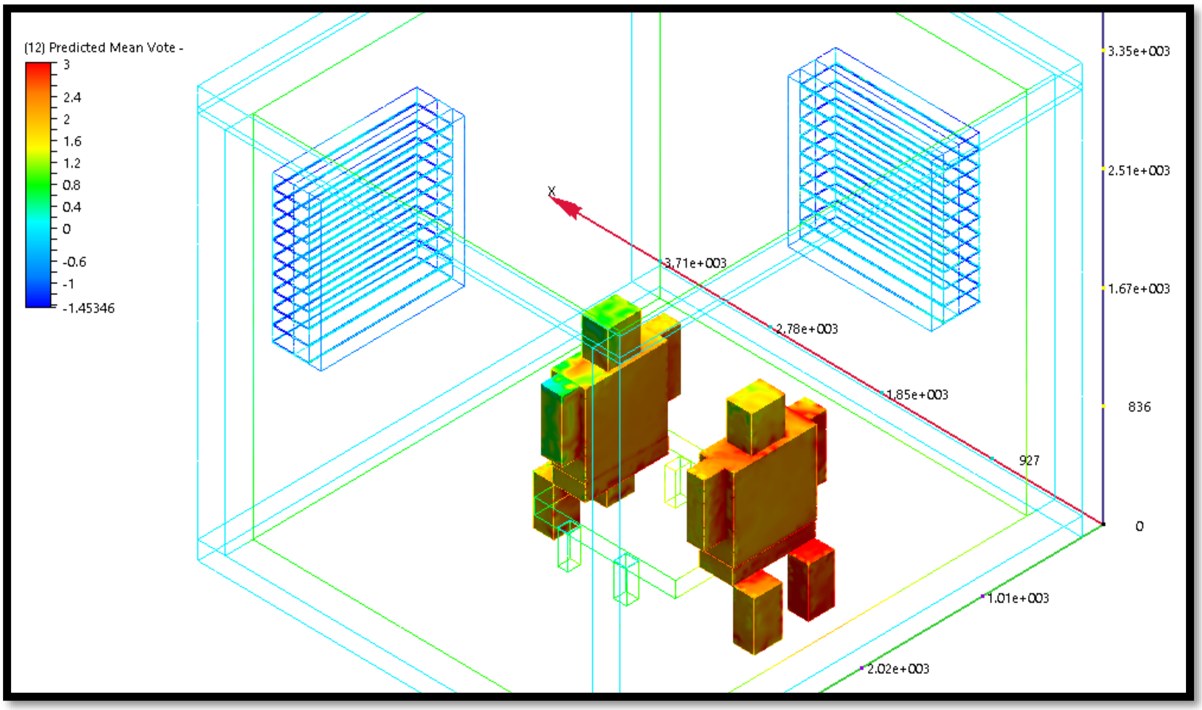

Figure 4. PMV result for Louvres window

Percentage of Person Dissatisfied (PPD)

PPD result for the Casement window indicates that the occupants closer to the air inlet express less than 25% level of dissatisfaction. While occupants farther from the air inlet expresses as high as 95% level of dissatisfaction. For the PPD prediction for the sliding window scenario, occupants express between 40 – 70 % levels of dissatisfaction while those further away from the inlet express up to 99% level of dissatisfaction. For the Awning/Top hung Window prediction, the result indicates that the occupants close to the air inlet express between 35 – 65 % levels of dissatisfaction while those further away from the inlet express up to 99% level of dissatisfaction. Prediction for the louver window indicates that the occupants directly opposite the inlets would express dissatisfaction as low as 10% while most of the occupants would express dissatisfaction ranging from 40% -90% depending on their location within the space (Figure 5 to 8).

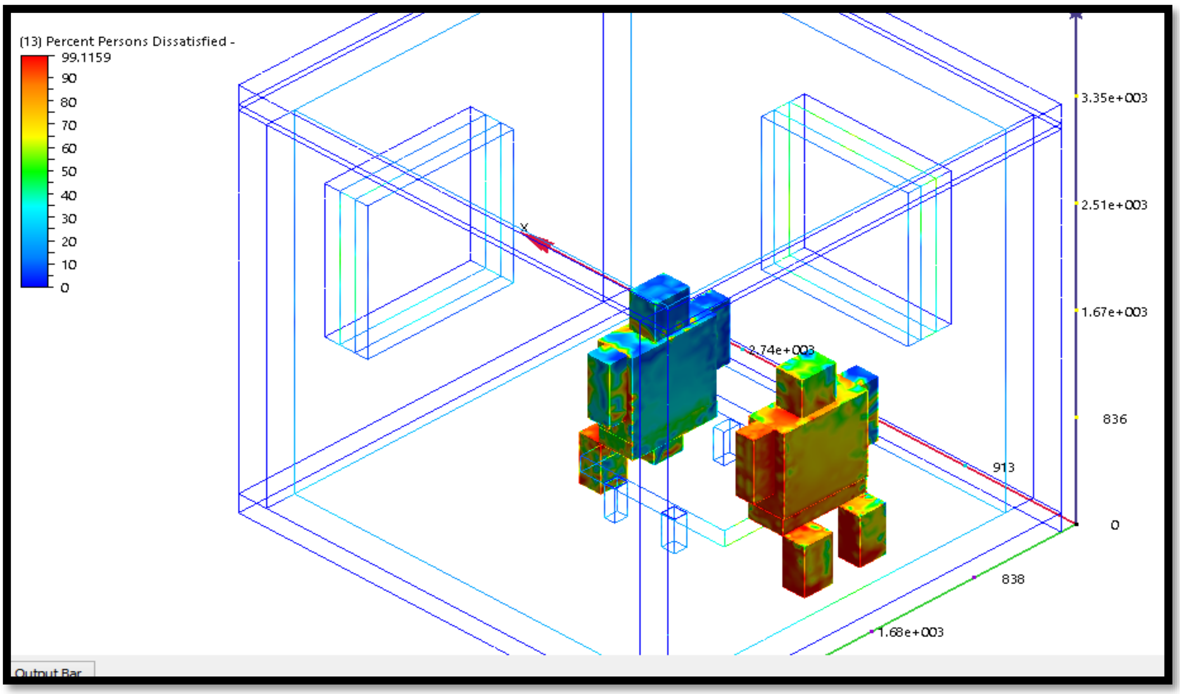

Figure 5. PPD prediction for casement window

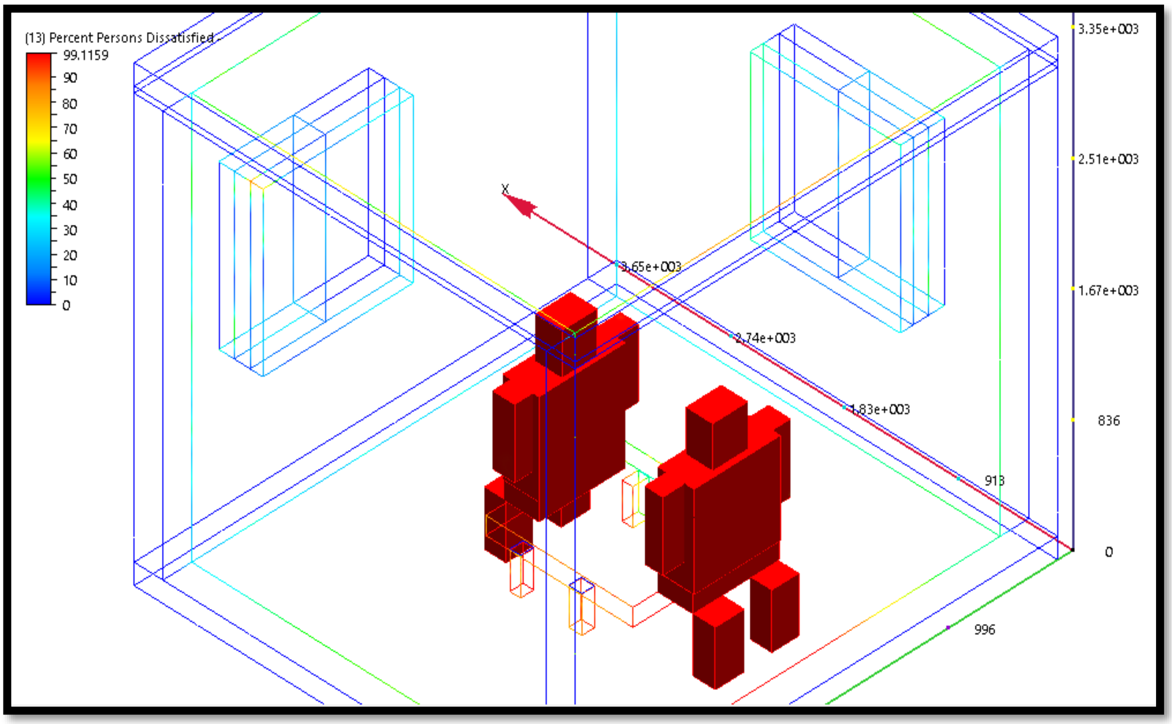

Figure 6. PPD prediction for the sliding Window

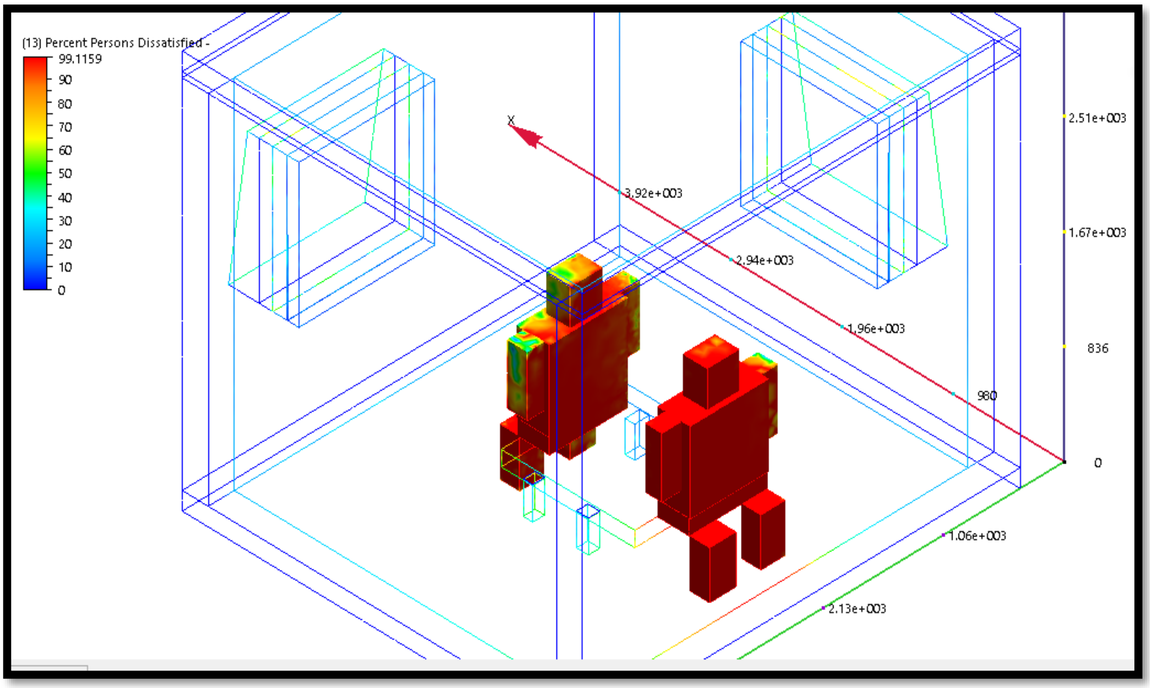

Figure 7. PPD prediction for Top hung window.

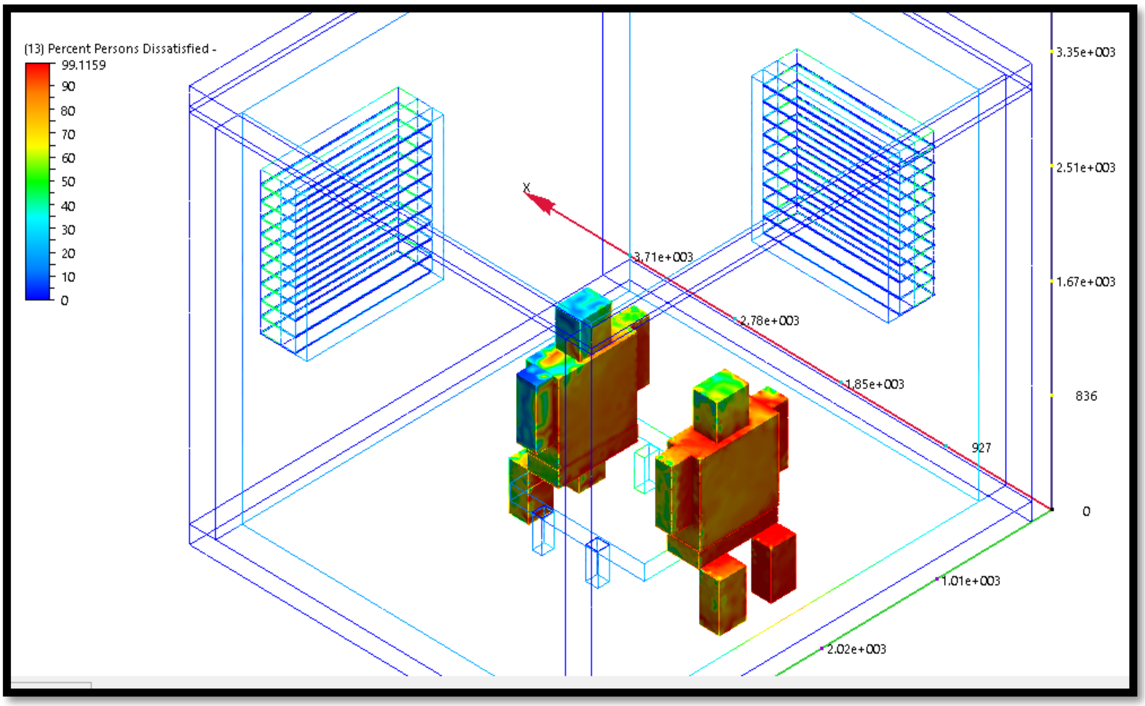

Figure 8. PPD prediction for Louvres window

Difference in Temperature Between Ankle and Head Positions

It is expected that the difference in temperature between ankle and head positions (for a seated occupant) should be within 2℃ (3.6 F) (ASHRAE, 2004; Premkumar, 2013). The result shows that two of the tested window types achieved this. The louvre window resulted in a difference 0.61℃, while the casement window recorded 1.2℃. On the other hand, the top-hung and horizontal sliding windows recorded temperature differences of 2.13℃ 3.34℃, which are above the stated standard.

Average Air Temperature

In order to achieve comfort, the average air temperature within the space should be between 22.77℃ and 25℃ (ASHRAE, 2004; Premkumar, 2013). The temperature statistics extracted from the result summary sheet of the simulation gives the mean value and standard deviation achieved with each of the window types. This shows that the average air temperature achieved with the use of casement window is 28.67%; for sliding window is 34.70%; for top-hung window is 30.54%; while that for louvre window is 27.66% (Table 4). Comparing this with the ASHRAE (2004) comfort limits of 22.77℃ and 25℃, it can be seen that the casement window exceeds the upper limit by 3.67℃; the sliding window by 9.70℃; the awing/top-hung window by 5.54℃; and the louvered window by 2.66℃ respectively.

Table 4. Summary report for Temperature

Casement

*** Statistics for Temp ***

Value Range [C]	Percent Volume
25.930000 - 26.566737	79.090618
26.566737 - 27.203475	12.361528
27.203475 - 27.840212	4.132276
27.840212 - 28.476950	1.398452
28.476950 - 29.113687	0.717623
29.113687 - 29.750424	0.378308
29.750424 - 30.387162	0.203896
30.387162 - 31.023899	0.137775
31.023899 - 31.660636	0.111934
31.660636 - 32.297374	0.114305
32.297374 - 32.934111	0.299723
32.934111 - 33.570849	0.238523
33.570849 - 34.207586	0.172389
34.207586 - 34.844323	0.151750
34.844323 - 35.481061	0.252040
35.481061 - 36.117798	0.107214
36.117798 - 36.754536	0.066787
36.754536 - 37.391273	0.038789
37.391273 - 38.028010	0.026045
38.028010 - 38.664748	0.000025
Mean Value = 28.667426	Standard Deviation = 3.285683

Sliding

*** Statistics for Temp ***

Value Range [C]	Percent Volume
25.930000 - 27.055700	52.129390
27.055700 - 28.181400	12.788364
28.181400 - 29.307099	10.067194
29.307099 - 30.432799	5.286108
30.432799 - 31.558499	4.223112
31.558499 - 32.684199	3.613451
32.684199 - 33.809898	3.080699
33.809898 - 34.935598	3.075816
34.935598 - 36.061298	1.905772
36.061298 - 37.186998	1.286623
37.186998 - 38.312698	0.601727
38.312698 - 39.438397	0.351385
39.438397 - 40.564097	0.181206
40.564097 - 41.689797	0.130211
41.689797 - 42.815497	0.097704
42.815497 - 43.941197	0.072092
43.941197 - 45.066896	0.292732
45.066896 - 46.192596	0.557252
46.192596 - 47.318296	0.132731
47.318296 - 48.443996	0.126431
Mean Value = 34.696939	Standard Deviation = 7.617205

Top-hung

*** Statistics for Temp ***

Value Range [C]	Percent Volume
25.930000 - 26.709670	76.613023
26.709670 - 27.489339	12.683531
27.489339 - 28.269009	4.255431
28.269009 - 29.048678	2.033989
29.048678 - 29.828348	1.242268
29.828348 - 30.608017	0.661954
30.608017 - 31.387687	0.425687
31.387687 - 32.167357	0.212685
32.167357 - 32.947026	0.252733
32.947026 - 33.726696	0.149362
33.726696 - 34.506365	0.104062
34.506365 - 35.286035	0.101280
35.286035 - 36.065704	0.118144
36.065704 - 36.845374	0.323341
36.845374 - 37.625044	0.164847
37.625044 - 38.404713	0.138543
38.404713 - 39.184383	0.260091
39.184383 - 39.964052	0.155990
39.964052 - 40.743722	0.049227
40.743722 - 41.523392	0.053809
Mean Value = 30.542693	Standard Deviation = 5.131379

Louvre

*** Statistics for Temp ***

Value Range [C]	Percent Volume
25.930000 - 26.634403	89.909239
26.634403 - 27.338805	4.960924
27.338805 - 28.043208	2.220502
28.043208 - 28.747611	0.785557
28.747611 - 29.452014	0.368436
29.452014 - 30.156416	0.188676
30.156416 - 30.860819	0.147387
30.860819 - 31.565222	0.117233
31.565222 - 32.269625	0.086992
32.269625 - 32.974027	0.061013
32.974027 - 33.678430	0.077725
33.678430 - 34.382833	0.188072
34.382833 - 35.087235	0.191324
35.087235 - 35.791638	0.131460
35.791638 - 36.496041	0.373441
36.496041 - 37.200444	0.091190
37.200444 - 37.904846	0.036896
37.904846 - 38.609249	0.011350
38.609249 - 39.313652	0.042927
39.313652 - 40.018054	0.009657
Mean Value = 27.661801	Standard Deviation = 3.251535

With this result, the louvre window performed best, while sliding window was the worst. However, none of the window types meets the ASHRAE standards. This does not suggest that none of the windows could meet this standard in reality since a dimension of 1200mm and 1200mm was used for the simulation. Larger window dimensions will result in differences.

Air Velocity

The standards also require that air velocity must be at or below 0.254m/s within 300mm of the walls and vertically between 150mm and 1800mm (ASHRAE, 2004; Premkumar, 2013). The result shows that the casement and louvre windows achieved this requirement in fairly large part of the modelled room. However, the horizontal sliding and top-hung windows did not achieve this in a large part of the room.

Mixing of Air in the Space

With regards to ASHRAE comfort limit for air mixing which rates the velocity magnitude for optimum airflow at 0.0762m/s (ASHRAE, 2004; Premkumar, 2013), the result of the simulation shows that the casement and louvre window exhibited less than 10% level of stagnation at velocity magnitude of 0.0762m/s. The top-hung aids air mixing to about 70 % of the sample volume, with little pockets of stagnation, while the sliding window on the other hand doesn't aid air mixing adequately (less than 5% mixing) at a velocity of 0.0762m/s creating large pockets of draughts in the sample volume.

Comparison Between Window Types

Based on the result, table 6 below gives a summary the performance of the window types in line with the research objectives, and with reference to the comfort limit conditions according to the ASHRAE Standard 55-2204 and ISO Standard 7730.

Table 6. Comparison between the Window samples

Comparison Parameters	**Casement Window**	**Horizontal Sliding Window**	**Awning/Top-hung Window**	**Louvered Window**
PMV	Slightly warm to hot lower body and slightly warm to neutral upper body	The occupant falls within the warm to hot region	Warm to hot lower body and slightly warm to warm upper body	Slightly warm to hot lower body and slightly warm to neutral upper body.
PPD (PPD)	Low	Very High	High	Low
Difference between Ankle and Head	Meets criteria	Doesn't meet criteria	Doesn't meet criteria	Meets Criteria
Mixing of Air	Good	Poor	Good	Very Good
Average Air temperature is between 22℃-25℃	Doesn't meet criteria	Doesn't meet criteria	Doesn't meet criteria	Doesn't meet criteria
Velocity must be at or below 0.254m/s	Most points with velocity of 0.254m/s.	Few points with velocity of 0.254m/s.	Many points with velocity of 0.254m/s.	Most points with velocity of 0.254m/s

CONCLUSION

Predictive Mean Vote (PMV) in spaces in Zaria will vary based on the window type used. This variation directly affects the PPD with the thermal comfort conditions within space. High PPD is associated with top-hung windows and the commonly used horizontal sliding window, while lower PPD is associated with louvre windows which are becoming extinct, and casement windows which are gradually returning to the market. Also, the predicted performance of casement and louver windows in Zaria meets most of the ASHRAE standard. It is therefore recommended that casement windows and louver windows be used in buildings in Zaria since they can be opened when ventilation is required for thermal comfort and closed is cooler periods when much airflow is not required.

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