THERMAL COMFORT MODEL DEVELOPMENT FOR OFFICE BUILDINGS WITH HYBRID DOWNDRAFT EVAPORATIVE COOLERS IN BAYERO UNIVERSITY KANO

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ABSTRACT

The numerous thermal comfort models developed for air-conditioned and free-running spaces are unsuitable for accurate prediction of thermal comfort of buildings equipped with hybrid downdraft evaporative cooling (HDEC) systems. This study attempts to develop a thermal comfort model for office buildings equipped with the HDEC in the new campus of Bayero University Kano. The windows of the office buildings were optimized using Taguchi analysis. The 3D model of the baseline office building using the optimum window-to-wall ratio (WWR) of 25% was developed and numerically analyzed using DesignBuilder CFD simulation. The numerical PMV_{opt} results were employed for training the thermal comfort model using the statistical software package Minitab 19. The validation shows a good agreement between the predicted results and the experimental data. The developed model could help building designers and engineers to make appropriate decisions at design stage regarding the thermal comfort of office buildings to be equipped with the HDEC systems.

Keywords: Thermal comfort, CFD simulation, Experimental study, Predicted mean vote, Thermal comfort model

INTRODUCTION

Around 40% of worldwide energy is consumed by the building sector, with a large percentage of that energy being utilized to ensure thermal comfort (Kim et al., 2016; Ravat et al., 2017; Sun et al., 2018). The term "thermal comfort" refers to a state of mind in which one is content with one's thermal surroundings (ASHRAE Standard-55, 2013; EN ISO 7730, 2005). Majority of people spend more than 80% of their time indoors. As a result, occupant comfort is linked to their well-being, productivity, and efficiency, making the study of thermal comfort in buildings vital (Mansor&Sheau-Ting, 2020).

Thermal comfort in buildings is a function of physical, environmental and social factors; therefore, its study is complicated. To study the thermal comfort of people in an occupied space, many thermal comfort models have been developed. According to International Standards such as ASHRAE-55, ISO 7730 and EN 15251, thermal comfort models were developed to statically or dynamically minimize thermal discomfort perceived by typical occupants in a moderate environment (WMO, 2011). Fanger's thermal comfort model and the adaptive comfort model are the two major models based on these static and dynamic classifications, respectively (ASHRAE Standard-55, 2013; EN 15251, 2007).

Many researchers have conducted thermal comfort studies using the adaptive comfort model. Humphreys (1976) conducted a thermal comfort study in which an adaptive comfort model was employed to explain the thermal comfort scenarios. de Dear, *et al.* (1998) used a global database of thermal comfort field studies to propose the use of adaptive comfort model in a more systematic form. The focus on the adaptive comfort model for determining the thermal comfort of people by researchers is globally increasing, especially in Australia (de Dear et al, 2015), America (Schiller *et al.*, 1998), Japan (Takasu*et al.*, 2017; Mustapha *et al.*, 2016), Europe (Yun et al., 2016; Montazami*et al.*, 2017), etc.

The daptive comfort model is based on the outdoor temperature (Aiman*et al*., 2018). The correlation between the indoor comfort temperature and the outdoor temperature is climate dependent and the acceptability limit employed is most suitable for free-running buildings.

Fanger's model has been used by many researchers for studying the thermal comfort of occupied spaces that are conditioned by mechanical air handling systems or natural ventilation. To suit certain situations, some researchers have modified the Fanger's thermal comfort model. Han *et al*. (2014) analyzed and simplified the major parameters of Predictive Mean Vote (PMV) to avert measuring some of the parameters such as the relative humidity and air velocity. Yao *et al*. (2009) introduced an adaptive coefficient into the PMV model based on the black box theory to address the issues of overestimating and underestimating the PMV model. Fanger and Toftun (2002) introduced a correction factor into the PMV because of the speculation that the PMV overestimates the thermal sensation of occupants in naturally ventilated buildings.

Despite the numerous thermal comfort models developed for both free-running and mechanically ventilated buildings, the development or modification of the thermal comfort models to suit the thermal comfort scenario of a space conditioned by evaporative cooling systems is lacking. Therefore, utilizing the Fanger's comfort model, a thermal comfort model for an office building equipped with a hybrid downdraft evaporative cooler (HDEC) was developed.

Case Study Area

Bayero University Kano is located in the savannah region of North-western Nigeria, at latitude 12.05°N, longitude 8.53°E, and an altitude of 481 m above sea level. The study building is 4m x 3.7m x 3m and is placed in the university's excellence center. The office building is a one-zone structure with 0.068 people/m^2 occupancy rate.

MATERIALS AND METHODS

Experimental test of the HDEC system

The HDEC was designed considering the optimum cooling load of the sampled office blocks in the New Campus of Bayero University Kano (BUK). The HDEC system was then fabricated at the Faculty of Engineering workshop and installed in one of the site offices of the Centre of Excellence of BUK as shown in Figure 1.

Figure 1: HDEC integrated into an office building

Experiment was conducted for three months which spanned from September to November, 2020. Hourly readings of the HDEC outlet and the indoor parameters were taken using digital probe airflow meter with model No. TA430 and Serial No.TA4301025005 and a set of hygrometer. The definition sketch where the measurements were taken is shown in Figure 2.

Readings of the HDEC outlet parameters T_e and Q_e, and the indoor parameters $T_i, V_i, RH_i,$ andT_{mr} were taken from 8:00am to 4:00pm for a total of 24 days for a span of three months: September, October, and November 2020.

Figure 2: Hygrometer at the centre of office room at 1.1m above floor level

Where: $T_e =$ HDEC outlet temperature, °C; $Q_e =$ HDEC outlet lowrate, litre/sec; $T_i =$ Indoor temperature of the office room, °C; $V_i =$ Indoor temperature of the office room, °C; $RH_i =$ Indoor relative humidity of the office room, %; $T_{mr} =$ Mean radiant temperature of the office room, °C.

Determination of the experimental thermal comfort of the office building

Daily averages of the indoor experimental data: indoor temperature (T_i) , indoor air velocity (V_i) , and indoor relative humidity (RH_i) were measured and recorded. For a clothed person sitting and doing light work typical for an academic office and, being thermally comfortable without activating any of the body defense mechanisms, an assumed metabolic rate (M) of 1.0 met (58.2 W/m^2) and a clothing insulation of 0.5 clo (0.08 °C.m^2/W) were used while the mean radiant temperature (T_{mr}) was taken to be equal to the indoor dry bulb temperature (T_i) as recommended by (ASHRAE Standard-55, 2013). These six environmental and personal thermal comfort parameters were uploaded into the Centre for Built Environment (CBE) thermal comfort tool (Federico *et al.*, 2020) for the computation of the Predicted Mean Vote(PMV_e).

Numerical determination of thermal comfort of the office building

Study has shown that the window geometry of a space to be conditioned by the HDEC system significantly affects the indoor thermal comfort. Therefore, the development of the thermal comfort model is based on the optimum window geometry of the office building model.

Determination of optimum window geometry of the office building using Taguchi analysis

Taguchi method was employed for selecting the optimum control factors used for the optimization of the window geometry based on the window-to-wall area ratio (WWR). Based on the architectural information obtained from the physical planning unit of BUK and the personal inspection concerning the sampled office buildings, the control factors and their levels are presented in Table 1.

Table 1: Optimization control factors with their levels

Control factors	Levels		
	1	2	3
Room volume, $R_v(m^3)$	34.60	96.60	280.38
HDEC exit air temperature, T_e(°C)	24.82	25.74	26.52
HDEC exit air flow rate, $Q_e(m^3/s)$	0.06363	0.07857	0.10404
Indoor air temperature, T_i(°C)	25.36	26.38	27.18
Indoor relative humidity, RH_i(%)	74.79	79.01	82.16
Indoor air velocity, $V_i(m/s)$	0.018	0.039	0.067

For the selection of the optimum control factors with their corresponding levels, smaller-the-better signal-to-noise (S/N) ratio approach was adopted. The optimum control factors for the WWR optimization are presented in Table 2.

Table 2: Optimum control factors for WWR optimization

S/N	Control Factors	Level	Value
1	Room volume, $R_v(m^3)$	1	34.60
2	HDEC exit air temperature, $T_e(°C)$	3	26.52
3	HDEC exit air flow rate, $Q_e(m^3/s)$	2	0.07857
4	Indoor air temperature, $T_i(°C)$	3	27.18
5	Indoor relative humidity, $RH_i(\%)$	2	79.01
6	Indoor air velocity, $V_i(m/s)$	2	0.039

The optimization of the WWR was carried out on the building model which was created using DesignBuilder software. The zone level and the integrated HDEC-office models are shown in Figures 3 and 4 respectively.

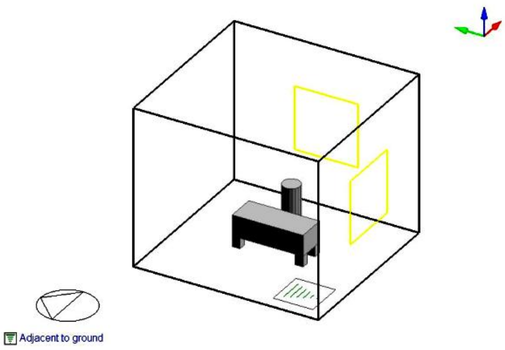

Figure 3: 3D zone level of base case model

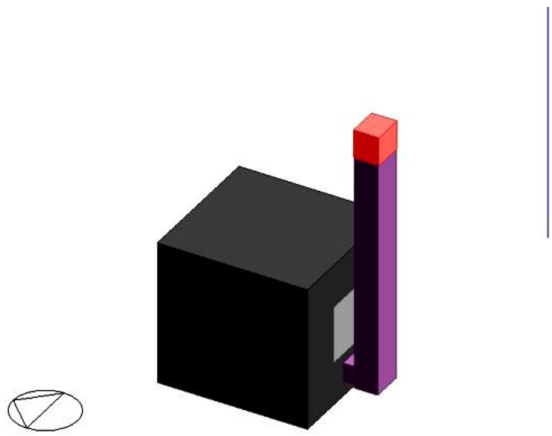

Figure 4: 3D integrated HDEC-office model

The optimization of the WWR was carried out on the office building model using two ventilation strategies: adjacent ventilation (AV) and cross ventilation (CV). For each of these strategies, DesignBuilder parametric analysis was employed by keeping the optimum control factors constant while varying the WWR from 10% to 50% step 5%. Using the appropriate boundary conditions, DesignBuilder CFD simulation was then carried out to determine the optimum WWR using the thermal comfort PMV as the optimization objective function.

RESULTS AND DISCUSSION

The thermal comfort band from -0.5 to +0.5 in Figure 5 represents a region on the 7-point thermal sensation scale where the office occupants are thermally comfortable (ASHRAE Standard-55, 2013).

Based on ASHRAE recommended thermal comfort range of -0.5 to +0.5 on the thermal sensation scale, thermal comfort was achieved in 37.5% of the test period as shown in Figure 5. Thermal comfort was not achieved in the remaining days which might be attributed to the high relative humidity recorded in the experimental test office building. This agreed with ASHRAE Standard-55 (2013) and the reported work of Francesca *et al*. (2013) and Zhibin*et al*. (2019) who stated that in a natural ventilation setting, building occupants would be thermally comfortable when the indoor temperature ranges from 23℃ - 27℃ and the relative humidity ranges from 30% to 70%.

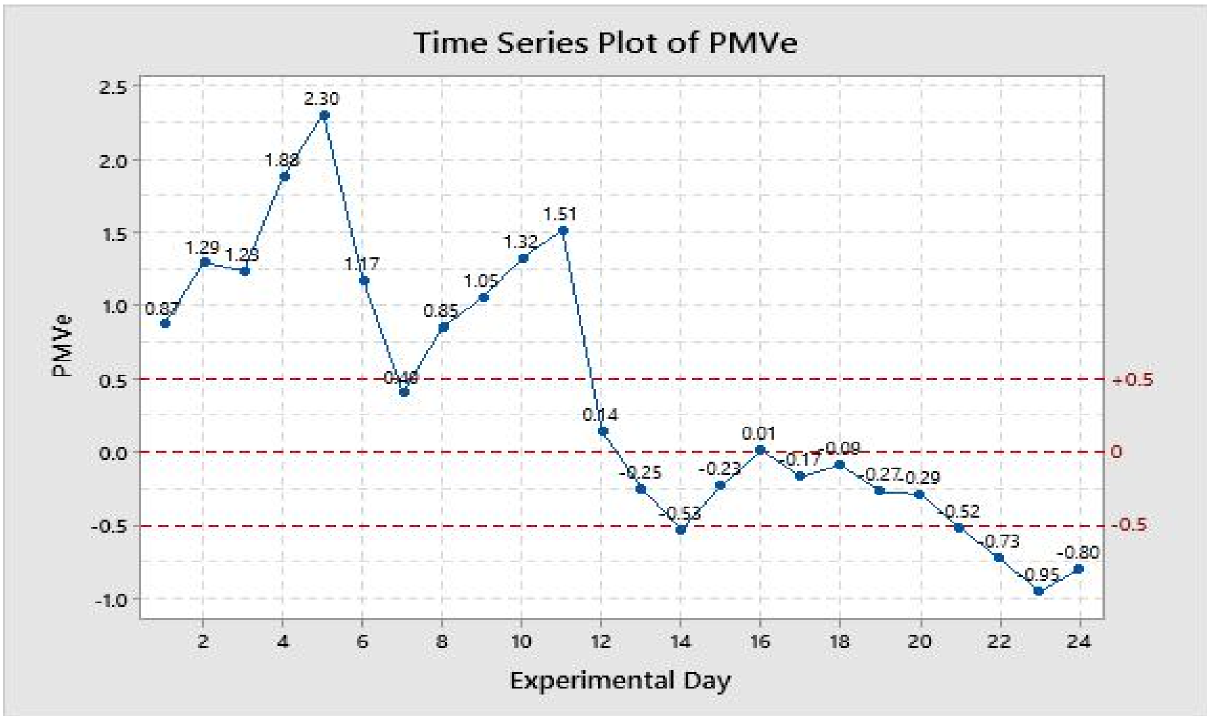

Figure 5: Plot of experimental PMV_e

The results of absolute PMV values of each of the WWR for AV and CV strategies were plotted on the plot in Figure 6.

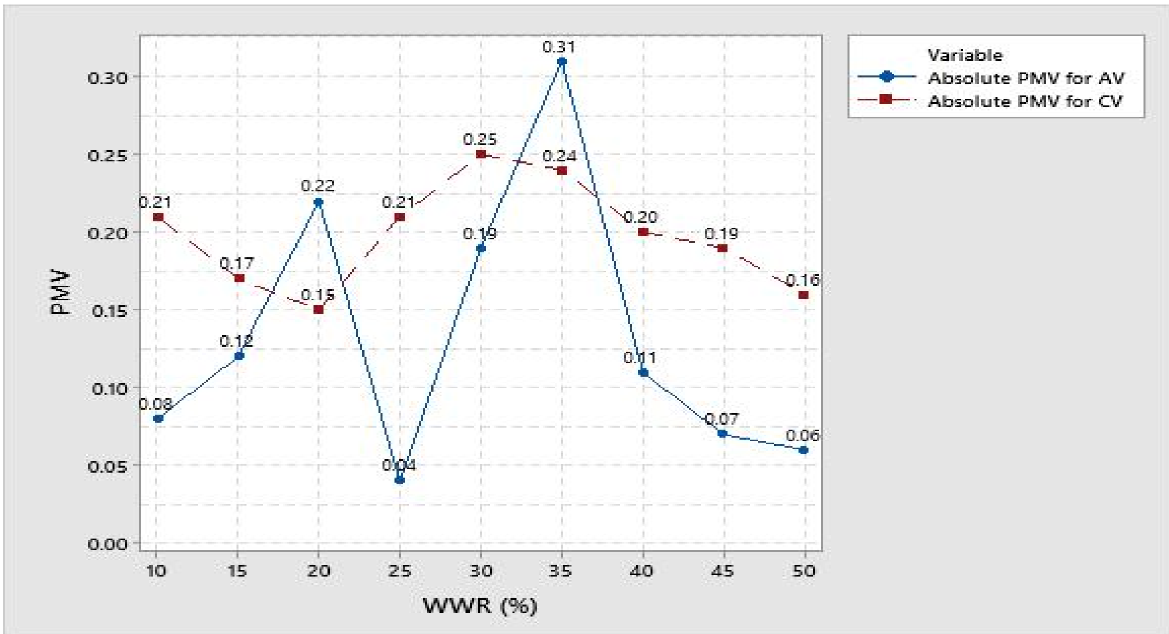

Figure 6: Absolute PMV vs WWR for AV and CV strategies

Figure 6 shows that the optima WWR for the AV and CV strategies are 25% and 20% respectively. These findings agreed with the reported work of Korantenget *al.* (2015) who stated that a WWR of 10%-40% for naturally ventilated building give an enhanced thermal comfort. Lee *et al*. (2012) and Shaeri*et al*. (2019) 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 20%-30% and exactly 25% respectively.

The numerical results of the thermal comfort (PMV_{opt}) using the optimum WWR of 25% with the pertinent indoor parameters are shown in Figure 7.

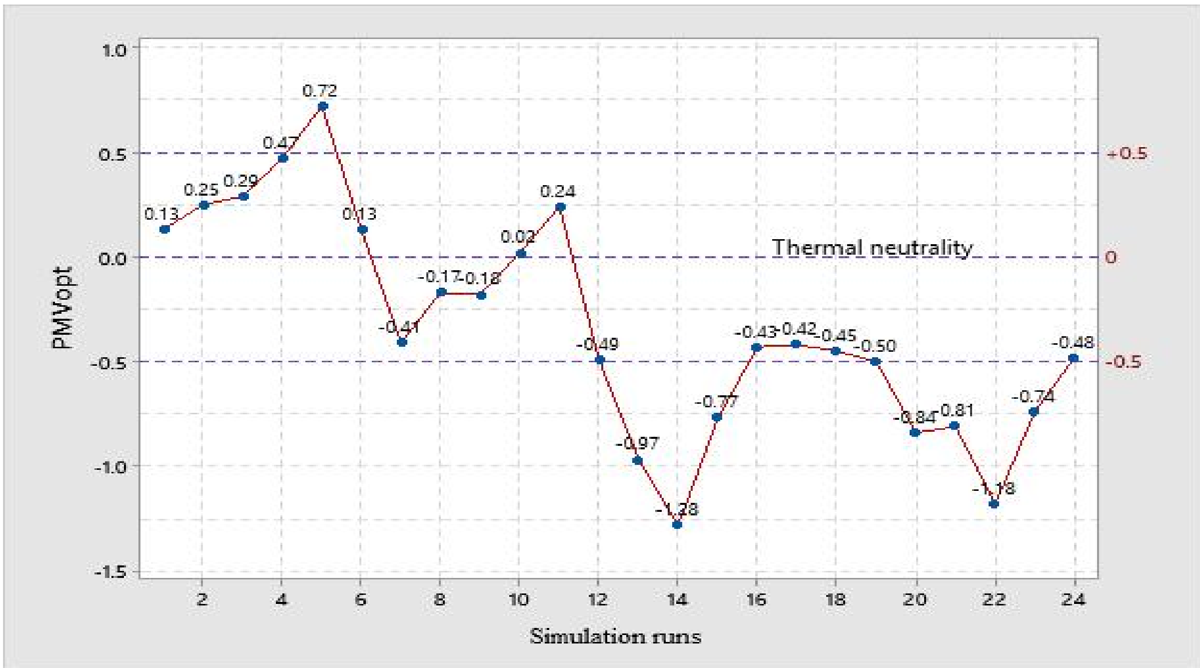

Figure 7: Simulation results of $\mathbf{PMV_{opt}}$

Figure 7 shows that thermal comfort PMV_{opt} was achieved in 16 experimental days based on ASHRAE recommended range of $-0.5 \leq PMV \leq +0.5$. This might be attributed to the use of the optimum WWR of 25% in the office building model. This represents about 66.7% of the experimental days which signified an increase of about 29.2% over the 37.5% obtained when the actual WWR of the office building was used for the analysis. These findings were supported by the study conducted by Lee et al. (2012) and Koranteng et al. (2015 who the WWR for optimal comfort in a free-running building were 25% and 10%-40% respectively.

The regression analysis of the pertinent independent variables with $P \leq 0.05$ against the dependent variable (PMV_{opt}) using Minitab 19 software shows that the predictive thermal comfort model developed is:

$$PMV_{opt} = -5.52 + 0.0964T_e - 0.00038RH_i + 1.335T_i$$

The coefficient of determination (R^2) is 87.9% which is an indication that 87.9% variability in the dependent variable (PMV_{opt}) could be explained by the independent variablesT_e, RH_i, and T_i.

The results of validating the thermal comfort model developed with the experimental results were shown on the line of best fit in Figure 8. The Root Mean Squared Error (RMSE) between the predicted PMV_p and the experimental PMV_e is 0.832.

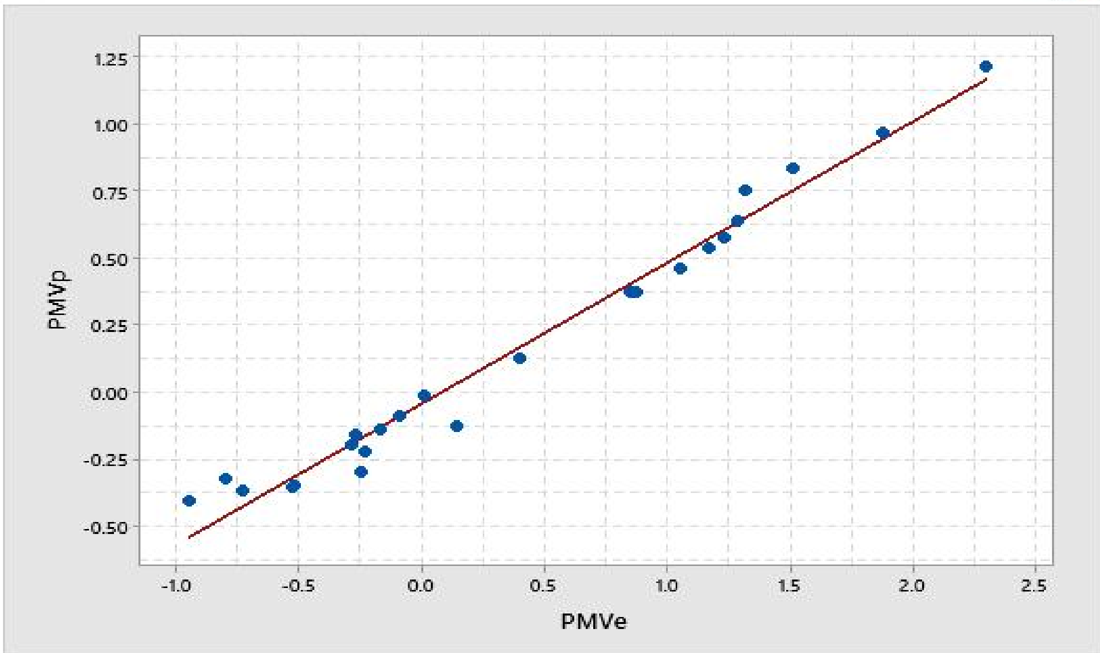

Figure 8: Agreement between Predicted and Experimental PMV Results

The P-value of the validation of the predicted results against the experimental results was 0.00 while the coefficient of correlation was 0.987. The line of best fit shown in Figure 10 indicates a good agreement between the predicted and the experimental values at 95% confidence level. The RMSE value of 0.832 further confirmed the agreement between the predicted and the experimental results.

CONCLUSION

In this paper, a a thermal comfort model was developed to predict the thermal comfort of office buildings equipped with HDEC at Bayero University Kano, Nigeria. The optimum window geometry of the office buildings in terms of WWR was numerically determined to be 25%. The integrated HDEC-office building modelled was simulated using DesignBuilder CFD software and the numerical thermal comfort PMV results were used to train the thermal comfort model. The thermal comfort model developed has high inference and predictive powers because of the high coefficient of determination (R^2) of 87.9% and RMSE of 0.832 respectively. The model developed was validated against the experimental results using the statistical software package Minitab 19. There is a significant correlation between the numerical and the experimental results ($r = 0.987,\ P = 0.00$) at 95% confidence level.

Hence, the developed thermal comfort model can help building designers and engineers to make appropriate decisions at the design stage regarding the window geometry and thermal comfort of office buildings to be equipped with the HDEC systems.

REFERENCES

Aiman, A., Dariusz, A., Adrian, P., Behdad, M. (2018). The Impact of the Thermal Comfort Models on the Prediction of Building Energy Consumption, *Sustainability*, 10(3609), 1-7.

ASHRAE-55. (2013). *Thermal Environmental Condition for Human Occupancy.* Atlanta: American Society of Heating, Refrigeration and Air Conditioning Engineers.

de Dear, R.J., Brager, G.S., Reardon, J., Nicol, F. (1998). Developing an Adaptive Model of Thermal Comfort and Preference/discussion", *ASHRAE Trans*. 104-145.

de Dear, R.J., Kim, J., Candido, C., Deuble, M. (2015). Adaptive Thermal Comfort in Australian School Classrooms", *Build. Res. Inf.*, 43 (3), 383–398.

EN 15251 (2007). Indoor Environmental Criteria for Design and Calculation of Energy Performance of Buildings. CEN, Brussels, Belgium.

EN ISO 7730 (2005). Ergonomics of the Thermal Environment: Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD indices and Local Thermal Comfort Criteria". *International Organization of Standardization*, Geneva.

Fanger, P.O., Toftum, J. (2002). Extension of the PMV Model to Non-Air Conditioned Buildings in Warm Climates, *Energy Build.*, 34, 533-536.

Federico, T., Stefano, S., Toby, C., Tyler, H. (2020). CBS Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. SoftwareX 12(2020) 100563.

Francesca, R., Elvira, I., Boris, I. (2013). PMV-PPD and Acceptability in Naturally Ventilated Schools, *Building and Environment*, 67, 129-137.

Han, H., Lee, J., Kim, J., Jang, C., Jeong, H. (2014). Thermal Comfort Control based on a Simplified Predicted Mean Vote Index. The 6th International Conference on Applied Energy-ICAE2014, *Energy Procedia,* 970-974.

Kim, S., Zadeh, P.A., Staub-French, S., Froese, T., B.T. Cavka, B.T. (2016). Assessment of the Impact of Window Size, Position and Orientation of Building Energy Load using BIM, *International Conference on Sustainable Design, Engineering and Construction,*1324 –1332.

Koranteng, C., Essel, C., Nkrumah, J. (2015). Paaive Analysis of the Effect of Window Size and Position on Indoor Comfort for Residential Rooms in Kumasi, Ghana, *International Advanced Research Journal in Science, Engineering and Technology*, 2(10), 114-120.

Lee, M., Mui, K., Wong, L., Chen, W., Lee, E., Cheung, C. (2012). Student Learning Performance and Indoor Environmental Quality (IEQ) in Air-Conditioned University Teaching Rooms. *Building and Environment*, 49, 238-244.

M.A. Humphreys M.A. (1976). Field Studies of Thermal Comfort Compared and Applied, Serv.

Mansor, R., Sheau-Ting, L., (2020). Criteria for Occupants Well-being: A Qualitative Study of Malaysian Office Buildings. *Building and Environment.*

Montazami, A., Gaterell, M., Nicol, F., Lumley, M., Thoua, C. (2017). Impact of Social Background and Behaviour on Children's Thermal Comfort, *Build. Environ.* 122, 422–434.

Mustapha, M.S., Zaki, S.A., Rijal, H.B., Hagishima, A., Ali, M.S.M. (2016). Thermal Comfort and Occupant Adaptive Behaviour in Japanese University Buildings with Free Running and Cooling Mode Offices During Summer, *Build. Environ*, 105, 332–342.

Ravat, V., Shivakar, S., Biplab, D., Sel, B. (2017). Effect of Orientation of Window on Building Heat Load: Perspective of N-E India, *Material Science and Engineering. India: IOP Conference Series*.

Schiller, G., Arens, F.A., Bauman, F., Benton, C., Fountain, M., Doherty, T. (1998). A Field Study of Thermal

Environments and Comfort in Office Buildings, *ASHRAE Trans*. 94.

Shaeri, J., Habibi, A., Yaghoubi, M., Chokhachian, A. (2019). The Optimum Window-to-Wall Ratio in Office Buildings in Hot-Humid, Hot-Dry, and Cold Climates in Iran, .*Environments*, 6, 45-61.

Sun, Y., Yupeng, W., Wilson, R. (2018). A Review of Thermal and Optical Characteristics of Complex Window Systems and their Building Performance Prediction, *Applied Energy*, 222 (729-742).

Takasu, M., Ooka, R., Rijal, H.B., Indraganti, M., Singh, M.K. (2017). Study on Adaptive Thermal Comfort in Japanese Offices Under Various Operation Modes, *Build. and Environ.*, 118, 273–288.

World Meteorological Organization, (2011).Daily Climate Weather Data,

www.geodata.us/weather/place.php?Usaf=650460...C=Nigeria.

Yao, R., Li, B., Liu, J. (2009). A Theoretical Adaptive Model of Thermal Comfort – Adaptive Predicted Mean Vote (aPMV), *Build. Environ.*, 44, 2089-2096.

Yun, G.Y. Lee, J.H., Steemers, K. (2016). Extending the Applicability of the Adaptive Comfort Model to the Control of Air-Conditioning Systems, *Build. Environ*, 105, 13–23.

Zhibin, W., Nianping, L., Pawel, W., Jingqing, P., Jingqing, L. (2019). Thermal Comfort in Naturally Ventilated Dormitory Buildings in Changsha, China, *Energy and Building*, 186, 56-70.