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Architectural Window Design Effect on Occupant Thermal Comfort and Low Energy Consmption in Residential Buildings

Chime Charles[1], Okafor Marcellinus[2], Essaghah Arthur[3]
[1]Department of Architecture, Delta State University of Science and Technology, Ozoro.
[2]Department of Architecture, Imo State University, Owerri.
[3]Department of Urban and Regional Planning, Delta State University of Science and Technology, Ozoro.

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ABSTRACT
The discomfort of indoor environmental condition in occupied spaces in buildings due to window types has escalated the combined effect of high solar radiation and humidity levels in the warm-humid climate which is an impact from climate change. The discomfort faced by occupants of buildings are less effective air flow; which cannot ensure personal thermal comfort and expel indoor air temperature that can impact on occupants performance. As a result, these have contributed to use of artificial means to provide a comfortable thermal environment at high energy consumption in the warm-humid climate zone. The study is divided into two parts: the first part was carried out through direct physical measurements by using sensors (data logger) to monitor indoor air temperatures, which will be used to identify the frequency of indoor comfort temperature range for occupant thermal comfort in office building in warm humid climate. The findings show that optimized window design is vital in achieving thermal comfort with no additional financial investment and a reduction on dependence on air conditioning coupled with reduction of discomfort periods in indoor environment.
The descriptive analysis result shows that the sliding window has a mean value of 6.23, projected 5.10, casement 4.60, louvre 3.90, and casement with vent 3.80. The standard deviation of sliding window is 0.25, projected 0.36, casement 0.17, louvre 0.45 and casement with vent 0.00. The sliding window has a mean value of 6.23 and standard deviation of 0.25, which indicates that occupant thermal comfort level in sliding window is lower. While, casement with vent window has a mean value of 3.80 and standard deviation of 0.00, and it indicates that occupant thermal comfort level in casement with vent window is higher.The Duncan result on the comparative analysis of effect of window types on occupant's perception of thermal comfort in naturally ventilated buildings in the study area. The casement with vent, and louvre windows were cooler. While casement and projected were moderate then sliding window had warmer occupant thermal comfort perception level. Recommendations were made for casement-with-vent windows to be used for the effective design for low energy consumption in building and achieving occupant thermal comfort.

Keywords: Energy Efficient Building, Indoor Air Temperature, Occupant Thermal Comfort, Ventilation, Window Types.

I. INTRODUCTION

As part of energy conservation method, the understanding of performance of window types in naturally ventilated buildings is an important issue for building designers. The type of window fitted in the building has a direct influence on the pattern of flow of air in the interior of the building. Air movement can increase the heat convection between the human body and the ambient environment, so that it takes away the heat by evaporating perspiration. The average skin temperature is 32°C-34°C when people are doing light activity, and the physical evaporation rate is based on air velocity and vapour press. The increase of air velocity can speed up the evaporation rate; while the evaporation rate will be decreased merely under high vapour pressure. Providing a cooling effect by increasing air

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movement can be achieved as the air temperature is lower than skin temperature (Diogu & Okonkwo, 2005; Szokolay, 2004). Therefore, providing air movement is an important method to reduce cooling load and achieve comfort, especially in warm humid climates (Adebamowo et al., 2010).
However, the function of a building is to protect man against the weather and provide an environment that maintains his well-being (Anunobi et al., 2015). This emphasises the importance of building being both healthy as well as comfortable (Atolagbe, 2014; Olanipekun, 2014). The National Building Code (NBC, 2006) stated that the design of buildings accounts for both comfortable thermal indoor environment as well as obtaining the necessary air flow rate to secure a comfortable atmospheric indoor environment (NBC, 2006). Chartered Institute of Building Services Engineers (CIBSE, 2006) recorded that ventilation of occupied spaces in buildings has two primary purposes; to provide an acceptable indoor air quality (IAQ), which essentially is based on the supply of fresh air and the removal or dilution of indoor pollution concentration. The other is to provide thermal comfort by providing a direct cooling effect over the human body through convection and evaporation (CIBSE, 2006). Considering energy efficient buildings without mechanical cooling and ventilation, the air exchange rate provided by window ventilation is a crucial design variable (Heiselberg et al., 2001; NBC, 2006; Anunobi et al., 2015).

II. LITERATURE REVIEW

Thermal comfort is strongly related to thermal balance between the body's heat generations and the release of body heat into its surroundings. Human body continuously produces heat due to metabolic activities which is used as work and dissipated to surrounding to maintain the body temperature (achieve body thermal balance). A state of thermal balance of the body is when heat gains and losses to its surrounding are at equilibrium rate.Baker and Steemers (2000) stated that heat loss to the environment occurs predominantly by three mechanisms (radiation, convection and evaporation) and to a much lesser extent by conduction. Heat transfer between human body and its surrounding in a normal comfort condition is illustrated in Figure 1.

Basically, our body constantly produces heat from the consumption and digestion of food and the processes are known as metabolism of the energy produced in the body. There are only about 20% of energy produced in the body is utilized in useful work while remaining 80% must be dissipated to the environment (Baker & Steemers, 2000).

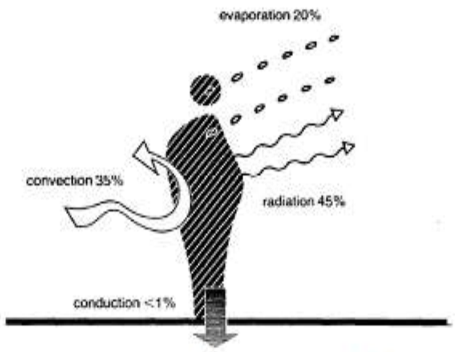

Figure 1: Body heat exchanges (Baker & Steemers, 2000)

Heat must be continuously dissipated and regulated to maintain normal body temperature at around 37ºC. Insufficient heat loss leads to overheating called hyperthermia, and excessive heat loss results in body cooling which is called hypothermia. An internal body temperature less than 28ºC can lead to serious cardiac arrhythmia and death; and temperature greater than 46ºC can cause irreversible brain damage. Therefore, the careful regulation of body temperature is critical to maintain body comfort and health (ASHRAE, 2010).

2.1 The effect of air flow speed and humidity on occupant comfort temperature

Aren et al., (1980) indicated occupant thermal sensation in the conditions of different air velocities. In a survey (in hot season) with the environmental condition at 50% relative humidity, 29°C indoor temperature and 1m/s air velocity, the occupants still feel comfortable when they are seated (1.3meter). The comfort temperature can reach 30°C, when the air velocity rises to 2m/s. A theoretical analysis by Fanga(1970) provided an equation of the relationship between the air velocity and the change of equivalent comfort temperature, in which the air flow should steady above 0.1m/s. That is because the result is meaningless when the air velocity is below 0.1m/s as the air movement related to the body is mainly driven by the body's movement or the natural convection (Equation 1, Figure 2).

$$T = 7 - \frac{50}{40 + 10v^{0.5}} \text{°C} \qquad \text{………………………… (1)}$$

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Where T (°C) is the change of equivalent comfort temperature and v (m/s) is air velocity.

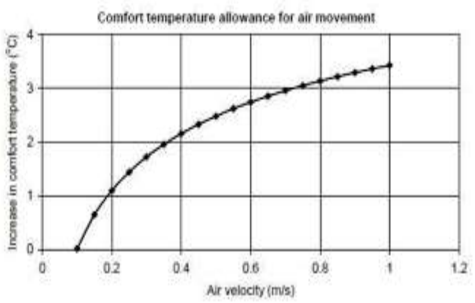

Figure 2: The correlation between comfort temperature and air flow speed (Nicol, 2004).

Humidity is also an important environmental factor that would influence occupant thermal comfort in warm humid climates like that of Asaba, and is closely related to indoor health issues and energy consumption. Apart from the influence on indoor air quality and health, the humidity would affect occupant thermal sensation under certain conditions. Humidity does not have a direct impact on occupant heat balance or physical response to the surrounding environment, but it would impact on the evaporation potential of the environment. At the high humidity level, it would reduce the evaporative capacity of the air, and decrease the ability of taking evaporative heat from the skin, which would cause the occupant to be uncomfortable (Givoni, 1998). Regarding the influence of high humidity on thermal comfort, Rigal et al., (2007) indicated that, when the relative humidity is above 70%, every 10% rise in relative humidity pushes up the air temperature by 0.4°C with the premise that the outdoor temperature is above 28°C. Nicol (2004) concluded that the primary impact of high humidity is narrowing the area of thermal comfort. Therefore, 1°C lower than the comfortable temperature should be provided when the relative humidity is high.

1.2 Thermal comfort indices

Air temperature and temperature of the immediate surroundings, humidity and speed of air flow in the local environment all modify the manner in which thermal comfort is experienced. For given values of aforementioned variables, thermal comfort level may be determined. Thermal comfort level can be defined in term of range of operative temperature and also by PMV and PPD index.

- **Operative temperature**

When calculating the indoor thermal climate, operative temperature (T_O) can be used as a simple measure for the heat loss from an occupant and also used to determine the temperature limit of the comfort zone (Adebamowo et al., 2013). A range of operative temperature provides an acceptable thermal environmental condition. In determining operative temperature, mean radiant temperature is seems to be a significant factor, especially in buildings which the envelopes are exposed to a strong solar radiation where conventional indoor temperature and humidity control cannot guarantee indoor comfort (Atolagbe, 2014). Note that, the mean radiant temperature has significant effects to the changes of operative temperature in dependence on the location. In addition, operative temperature is also time variable since indoor surface temperature is changing during the day depending on the outdoor climatic condition (Baker & Steemers, 2000). Operative temperature can be defined as the average of mean radiant temperature and dry bulb temperature weighted by their respective transfer coefficients (Auliciems & De Dear, 1986).

- **Predicted Mean Vote (PMV)**

A model named Predicted Mean Vote model was developed by Fanger (1970) which combines the six thermal comfort parameters into an index that can be used to predict thermal comfort level.

Table1: thermal sensation scale of ASHRAE and Fanger

Thermal Sensation	ASHRAE Scale	Fanger Scale
Hot	7	+3
Warm	6	+2
Slightly warm	5	+1
Neutral	4	0
Slightly cool	3	-1
Cool	2	-2
Cold	1	-3

Source: (Allan 2013)

PMV can be precisely determined if both environmental and individual parameters are correctly measured and only for steady-state conditions or minor fluctuations of variables.PMV index is derived on the basis of experimental conditions which are near thermal neutrality or slightly discomfort. The index provides a score that corresponds to ASHRAE thermal sensation scale

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and represents the average thermal sensation felt by a large group of people in a space Table 1, (Fanger, 1970; ASHRAE, 2009).

1.3 Study Area

The study area is Asaba in Delta State, Nigeria. Nigeria lies within 4^0N to 14^0N latitudes and 2^0E to 14.5^0E longitude. Asaba lies in Latitudes 6.2^0N of the Equator and longitude 6.73^0E of the Greenwich Meridian. The climate of Asaba is in warm humid climate zone with long wet season lasting from March to October that alternates with a shorter dry season that last from November to February. The climate is influenced by two prevailing air masses namely the south-west monsoon wind and then North-east trade wind. Annual rainfall in the Asaba area is up to 2500mm with double peak rainfall regime which takes place both in June and September. Annual average temperature is about 27^0C with no marked seasonal departure from the average. The natural vegetation of the area is rainforest with swamp forest occurring in flat-floured valleys and adjoining low lying areas that are seasonally or permanently water logged (NiMet 2006).

III. RESEARCH METHODOLOGY

The study is divided into two parts: the first part was carried out through direct physical measurements by using sensors (data logger) to monitor indoor air temperatures, which will be used to identify the frequency of indoor comfort temperature range.The second part will be carried out through obtaining data from the questionnaire survey to access the effect of indoor air temperature on thermal comfort of the occupants in naturally ventilated buildings.

3.1 Method and apparatus

The indoor climate LUTRON Thermo-Anemometer (AM4201A): multi-purpose pocket and hand held indoor climate tracker was utilized to measure the indoor climate conditions and this took place alongside questionnaire survey. The Data logger was ideal because it measures air velocity, air flow, and air temperature, with sensory accuracy of ±(3%+0.20m/s). 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. Occupants were asked to assess environmental conditions in terms of thermal comfort by filling in the questionnaire. The contents of the occupant questionnaire were developed from previous research on post-occupant evaluation by well-established researchers (Cohen et al., 2001; Yun and Steemers, 2008). In this questionnaire, occupants were asked to judge how they felt about the thermal environment on a typical 7-point ASHRAE sensation scale. Furthermore, occupants were asked to judge the acceptability of and preference for thermal conditions. A direct acceptability question asked occupants to gauge whether the current thermal condition was ‘acceptable’ or ‘unacceptable’. The McIntyre preference scale (Right now I want to be: cooler, warmer or no change) was used to investigate occupant preferences.

3.2 Characteristics of monitored building

The characterizations of the monitored buildings was based on the type of windows in the building which are casement window, casement with vent, sliding window, projected window and louvre windows respectively. In order to have adequate sample size required in addressing the research questions, sampling was focused on the residential buildings and the five window types as well as the occupants of the naturally ventilated buildings.

Plate1: Typical view naturally ventilated building in the study Area
Source: Field work (2022).

IV. DATA PRESENTATION AND ANALYSIS

This section present the data generated from the field work. The data generated from the questionnaire and physical measurement are sorted and arranged a way that is adequately fit for statistical analysis and interpretation using tables, bar charts, graphs, frequency distributions and percentages.

Question 1: How the occupants feel with the indoor temperature

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This question was asked to know how the respondents feel with the indoor temperature. The Table 4.38 shows how the occupants feel with the indoor temperature. The result has shown that about 4.30% of the respondents feel cold, 1.84% feel cool, 6.00% feel slightly cool, 2.00% feel neutral, 46.15% feel slightly warm, 10.92% feel warm and 70.61% feel hot. This shows that more of the respondents feel hot as shown in Figure 3.

Table 2: Occupant feeling with the indoor temperature

Occupant feeling with the Indoor temperature	frequency	percentage
Cold	28	4.30%
Cool	12	1.84%
Slightly cool	39	6.00%
Neutral	13	2.00%
Slightly warm	43	4.33%
Warm	71	10.92%
Hot	451	70.61%
Total	**650**	**100%**

Source: Field work (2022).

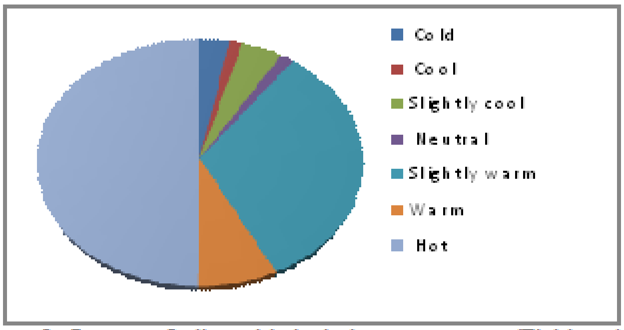

Figure 3: Occupant feeling with the indoor temperature (Field work 2022).

Question 2: Occupant thermal comfort level

This question was asked for respondents to indicate their level of thermal comfort. The Table 3; shows the thermal comfort level distribution of the respondents. The result has shown that about 0.92% of respondents were much too cool, 3.54% too cool, 2.00% cool, 4.76% ok, 18.92% warm, 64.92% too warm and 5.07% much tool warm. This shows that more of the respondents are feeling too warm as shown in Figure 4.

Table 3: Thermal comfort level distribution

Thermal comfort level	frequency	percentage
Much too cool	6	0.92%
Tool cool	22	3.54%
Comfortably cool	13	2.00%
Neither cool nor warm	31	4.76%
Comfortably warm	123	18.92%
Too warm	422	64.92%
Much too warm	33	5.07%
Total	**650**	**100%**

Source: Field work (2022).

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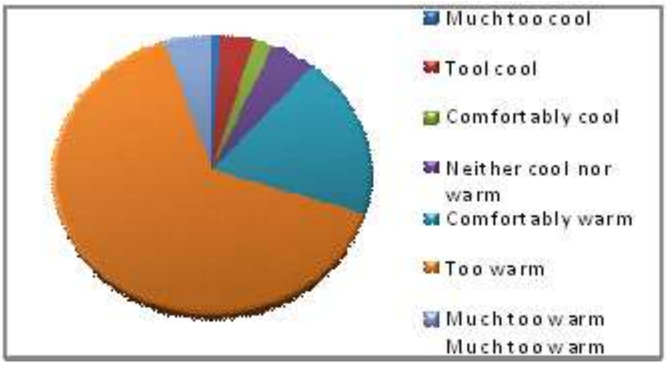

Question 3: Occupant preference of indoor temperature, (how would you like to be?)

This question was asked to know the distribution of how respondent would like to be. The Table 4; shows the occupant preference of indoor temperature. The result has shown that about 85.69% of respondents were cooler, 8.15% no change, 6.15% warmer. This shows that more of the respondents prefer to be cooler as shown in Figure 5.

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Table 4: occupant preference distribution of indoor temperature

Occupant preference of indoor temperature	frequency	percentage
Cooler	557	85.69%
No change	53	8.15%
Warmer	40	6.15%
Total	**650**	**100%**

Source: Field work (2022).

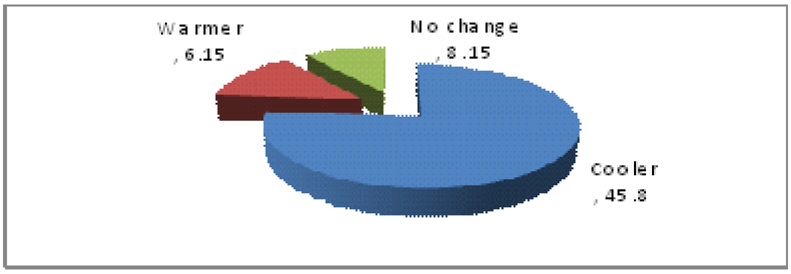

Figure 5: occupant preference distribution of indoor temperature (Field work 2022).

Question 4: occupant acceptability of the temperature

This question was asked to know the distribution of respondent's acceptability of the temperature. The Table 5; above shows the temperature acceptability distribution of the respondents. The result has shown that about 13.53% of the respondents accepted it while 86.46% of the respondents did not accept the indoor temperature. This shows that more of the respondents did not accept the indoor temperature as shown in Figure 6.

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Table 5: Temperature acceptability distribution

Temperature acceptability	frequency	percentage
Acceptable	88	13.53%
Not acceptable	562	86.46%
Total	**650**	**100%**

Source: Field work (2022).

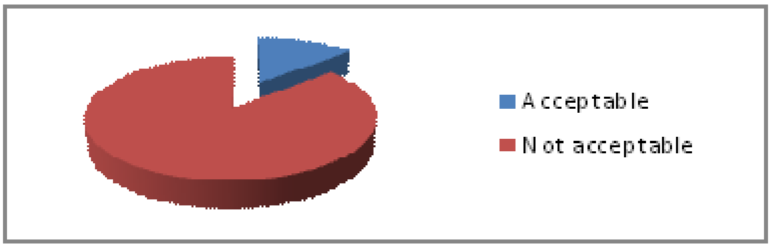

Figure 6: Temperature acceptability distribution (Field work 2022).

Question 5: Occupant preference of air temperature, (how would you like to have the air temperature.

This question was asked to know the distribution of how respondent would like to be. The Table 6; shows the occupant preference of air temperature. The result has shown that about 88.92% of respondents prefer lower, 6.30% exactly how it is now, and 4.76% prefer higher. This shows that more of the respondents prefer air temperature lower as shown in Figure 7.

Table 6: Occupant preference distribution of air temperature

Occupant preference of air temperature	frequency	percentage
Lower	578	88.92%
Exactly how it is now	41	6.30%
Higher	31	4.76%
Total	**650**	**100%**

Source: Field work (2022).

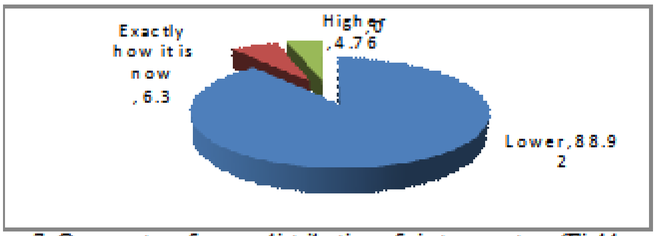

Figure 7: Occupant preference distribution of air temperature (Field work 2022).

Question 6: Occupant perception of air flow

This question was asked to know the distribution of how respondent feel about air flow. The Table 7; shows the occupant preference of air flow distribution of the respondents. The result has shown that about 0.92% of respondents were feeling cold, 1.38% cool, 1.53% slightly cool, 3.23% neutral, 4.92% slightly warm, 15.84% warm and 67.53% feeling hot. This shows that more of the respondents are feeling hot as shown in Figure 8.

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Table 7: Occupant perception of air flow distribution

Occupant perception of air flow	frequency	percentage
Cold	6	0.92%
Cool	9	1.38%
Slightly cool	10	1.53%
Neutral	21	3.23%
Slightly warm	32	4.92%
Warm	103	67.53%
Hot	439	15.84%
Total	**650**	**100%**

Source: Field work (2022).

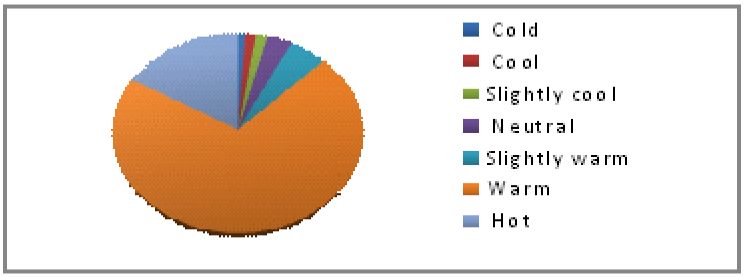

Figure 8: Occupant perception of air flow distribution (Field work 2022).

Question 7: Occupant preference of air movement, (how would you like to have the air movement.

This question was asked to know the distribution of how respondent would like to be (occupant preference of air movement). The Table 8; shows the occupant preference of air movement. The result has shown that about 3.53% of respondents prefer slower, 5.38% exactly how it is now, and 91.07% prefer faster air movement. This shows that more of the respondents prefer air faster air movement as shown in Figure 9.

Table 8: Occupant preference distribution of air movement

Occupant preference of air movement	frequency	percentage
Slower	23	3.53%
Exactly how it is now	35	5.38%
Faster	592	91.07%
Total	**650**	**100%**

Source: Field work (2022).

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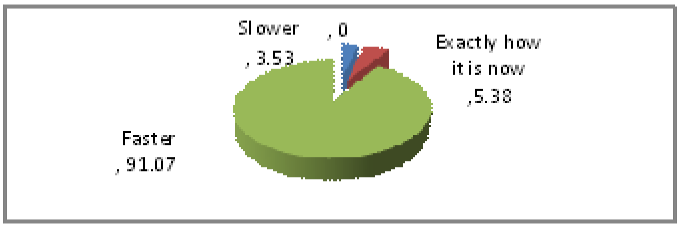
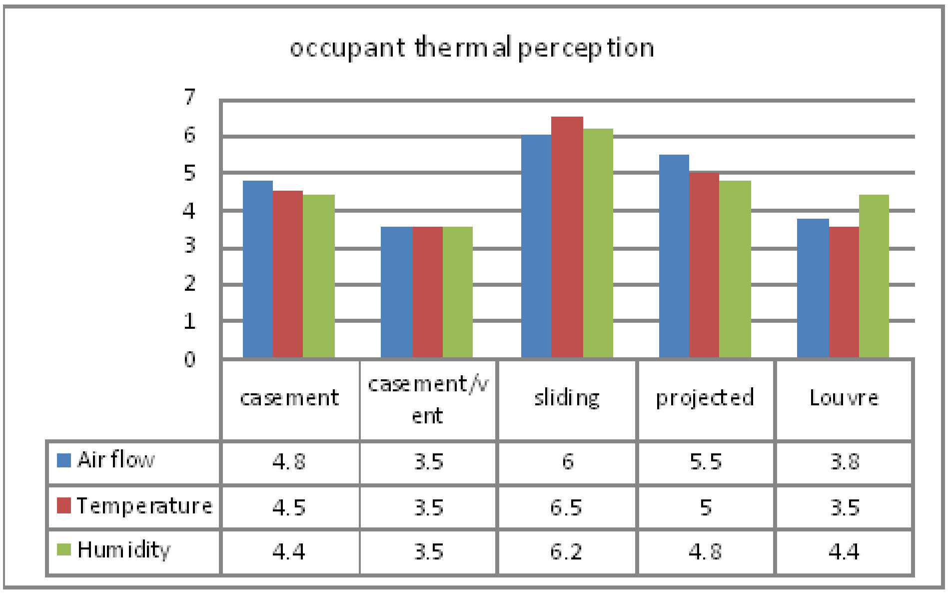


Figure 9: Occupant preference distribution of air movement (Field work 2022).

The thermal measurements indicate that indoor air temperatures range was 24–27ºC. The distributions of the globe temperature were within the range of 24.0-27.0°C. 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 58% to 85% and the air velocity range was 0.20 –1.25 m/s as shown in Figure 10.The result of occupant thermal perception emanating from naturally ventilated buildings with respect to the window types in the study area are shown in Figure 11.



	casement	casement/vent	sliding	projected	Louvre
Air flow	4.8	3.5	6	5.5	3.8
Temperature	4.5	3.5	6.5	5	3.5
Humidity	4.4	3.5	6.2	4.8	4.4

Figure 11: Result of occupant thermal perception emanating from buildings with casement (C), casement-with-vent (CV), sliding (S), projected (P), and louvre (L) (Field work 2022).

4.1 Analysis of Result

The result in table 9; discloses the mean and standard deviation of the occupant thermal comfort level considered in determining the effect of window types on occupant's thermal perception in naturally ventilated buildings in the study area. The descriptive analysis result shows that the sliding window has a mean value of 6.23, projected 5.10, casement 4.60, louvre 3.90, and casement with vent 3.80. The standard deviation of sliding window is 0.25, projected 0.36, casement 0.17, louvre 0.45 and casement with vent 0.00. The sliding window has a mean value of 6.23 and standard deviation of 0.25, which indicates that occupant thermal comfort level in sliding window is lower. While, casement with vent window has a mean value of 3.80 and standard deviation of 0.00, and it indicates that occupant thermal comfort level in casement with vent window is higher.

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Table 9: The descriptive analysis result on effect of window types on occupant's thermal perception in naturally ventilated buildings in the study area

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Casement	3	4.6000	.17321	.10000	4.1697	5.0303	4.50	4.80
Casement / vent	3	3.8000	.00000	.00000	3.8000	3.8000	3.80	3.80
Sliding	3	6.2333	.25166	.14530	5.6082	6.8585	6.00	6.50
Projected	3	5.1000	.36056	.20817	4.2043	5.9957	4.80	5.50
Lourve	3	3.9000	.45826	.26458	2.7616	5.0384	3.50	4.40
Total	15	4.7267	.95504	.24659	4.1978	5.2555	3.50	6.50

Source: ANOVA analysis output, SPSS 25

The result in table 10; has reported the p-value result for the ANOVA analysis on effect of window types on occupant's thermal perception in naturally ventilated buildings in the study area.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 effect of window types on occupant's thermal perception significantly differ in naturally ventilated buildings in the study area.

Table 10: The ANOVA analysis result on on effect of window types on occupant's thermal perception in naturally ventilated buildings in the study area

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	11.903	4	2.976	34.335	.000
Within Groups	.867	10	.087		
Total	12.769	14			

Source: ANOVA analysis output, SPSS 25

V. DISCUSSION OF RESULTS

In this research, occupants were asked to judge how they felt about the thermal environment on a typical 7-point ASHRAE sensation scale. In the occupants' thermal perception vote (Table 1), the numbers from 1 to 7 mean from much too cool to much too warm, while the number 4 was the neutral point, meaning neither cool nor warm. When collecting the data on the thermal perception vote with related temperature by the window types in the natural ventilated building, it can be seen (Figure 11) that in general the indoor temperature were towards hot and the majority votes were between 3.5 and 6.5, whereby it can be considered that the temperature was still acceptable. When the indoor air temperature rises above 26°C, some occupants would feel hot, and 30°C seems to be the top thermal threshold for occupants in the naturally ventilated buildings.Based on the results of occupant thermal perception vote in the naturally ventilated buildings, the indoor temperature was tending towards hot, but occupants were still satisfied by the indoor environmental condition. Thus, the top indoor air temperature threshold can be defined as 30°C; it was close to Givoni's (1994) comfort zone. In addition, when the indoor air temperature was higher than 28°C, none of windows was closed, occupants would feel hot and tried to increase the heat loss from the body, and keeping the window open can maintain the indoor air flow speed and improve their thermal comfort.

VI. CONCLUSIONS

Architectural window design has a massive impact on occupant thermal comfort and low energy consumption in buildings by providing the cooling and indoor air quality. The survey of the effect of window types on occupants' thermal perception shows the result on the thermal perception vote with related temperature by the window types in the natural ventilated building. It indicated that casement has 4.5, casement with vent 3.5, sliding 6.5, projected 5, and louvre 3.5. That in general the indoor temperature was towards hot and the majority votes were between 3.5 and 6.5, whereby it can be considered that the temperature was still acceptable. When the indoor air temperature rises above 26°C, some occupants would feel hot, and 30°C seems to be the top thermal threshold for occupants in the naturally ventilated buildings. The output of the analysis indicates that effect of window types on occupant's thermal perception significantly differ. The comparative analysis shows that casement-with-vent, and louvre windows provided a better indoor comfort environment. While casement and projected were moderate then sliding window had warmer occupant thermal comfort perception level. Replacing sliding windows with identically sized louvre or casement windows will almost double the cooling effect on occupants, and replacing projected windows with identically sized louvre or casement windows will increase the indoor air temperature. Therefore, it is recommended that; window types with high ventilation area percent should be used in naturally ventilated residential buildings to offer maximum ventilation. This will aid indoor air quality, effective ventilation, comfortable indoor environment and low energy consumption in building.

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