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The influence of air velocity on thermal performance of buildings in the tropics

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Abstract

The indoor buildings in the tropics need to be thermally comfortable for the well-being of the occupants. A thermal comfort survey was conducted in naturally ventilated buildings in southeast Nigeria to determine the influence of air velocity on their thermal performance. This was part of the general study where field work on students was carried out to determine their thermal comfort conditions. The survey was conducted during the rainy season and dry season. Data loggers were adopted to get objective measurements while a questionnaire was used to obtain objective responses. Result shows that the occupants were comfortable with air velocity at a temperature range between 26 -31^{o}C and were uncomfortable at temperatures below 25 °C and at temperatures above 31^{o}C.

Keywords: Air velocity; Building; Temperature; Thermal comfort

1. Introduction

One of the functions of a building is to provide an indoor environment suitable for human occupation. A building that has a sound architectural design can help to provide the microclimate required for the thermal comfort of the occupants. To maintain thermal comfort, buildings alone can generate about 30% of global carbon emission by cooling or heating the indoor spaces (Velier et al, 2017). The building sector contributes 19-50% of energy consumption with the likely outcome of rising to 60% in future ((López-Pérez, Flores-Prieto, and Ríos-Rojas, 2019). Cost can be saved, and carbon emission can be significantly reduced if the rate of use of air-conditioning systems can also be significantly reduced. Air movement plays an important role in the comfort of a building occupant by causing the feeling of freshness. This is achieved by increasing the rate of evaporation in a human body, especially at high humidity where evaporative cooling is the main source of heat loss from the body. Wind, therefore, reduces the adverse effects of thermal discomfort caused by high temperature and humidity. However, high air movement in a cool or cold environment may be perceived as draught, if the air temperature is less than skin temperature, it will significantly increase convective heat loss. While in winter high air movement may be viewed as unwelcome by building occupants, the opposite is the case in summer especially when the indoor temperature becomes unbearable. Airspeed is defined as 'the average of the instantaneous air velocity over an interval of time' (ASHRAE, 2017).

2. Literature Review

Results from many researchers have indicated the importance of air movement in an indoor environment, especially in the tropics. According to Zhang et al., (2017), inadequate ventilation is probably the most important reason for occupant discomfort in naturally ventilated buildings. (Mishra and Ramgopal, 2013) reviewed field studies on thermal comfort and reported that in very few cases where a great number of occupants voted in the zone of discomfort in naturally ventilated buildings, this was attributed to low air pressure recorded. Both the field measurements and the subjective investigation showed that the indoor air velocity might be a big problem in naturally ventilated classrooms, especially where there are inadequate openings. Fieldwork by Zhang et al., (2007) indicated that while only 46.1% of the

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respondents in classrooms felt the air velocity was just right (okay), 53.5% perceived the air too steady. A very low percentage of 0.5% felt the velocity should be less indicating a large majority would prefer more air.

Various researchers argued from their field works the need to increase airspeed above the one recommended by ASHRAE 55 and ISO 7730. Based on Fanger's laboratory experiment air velocity above 0.2m/s is not recommended by ASHRAE standard because of draft risk. Humphreys and Nicol (2002) argued that subjects could be comfortable at temperatures up to or even exceeding 30°C, in hot climates, especially if fans are used to increase indoor air. In separate studies carried out by Zhai, Arens, Elsworth, and Zhang (2017) and Cândido, de Dear, and Lamberts (2011) both observed that more people view air movement as positive in offices and in classrooms. Children requested slightly more air movement in the study conducted by Wigö (2013) in a school in Sweden during the spring and autumn when they were subjected to air velocity at irregular intervals. Schiavon, Yang, Donner, Chang, and Nazaroff (2017) assessed the thermal comfort conditions of Singaporean office workers in a tropical setting and observed that the occupants felt more thermally comfortable at the temperature of 26°C with the aid of fan than at 23°C when fan was not used. Some other researchers also supported the extension of the width of the comfort zone with increased air movement (Zhang et al., 2007). Arens et al. (2009) supports an increase in air velocity for thermal sensations from 0.7-1.5. Cândido et al., (2010) is of the opinion that the limit for a neutral-to-warm conditions be relaxed when the temperature is above 26°C. Zhai et al. (2015) confirmed that the air movement highly improves thermal comfort at 30°C.

Furthermore, fieldwork carried out on naturally ventilated residential buildings in Jos Nigeria by Ogbonna and Harris (2008) gave a low coefficient between air velocity and actual votes by occupants. The researcher attributed the likely cause to the low sensitivity of occupants to air velocity. McIntyre (1978) suggests that overall comfort deteriorates when the temperature reaches 30°C even when airspeed is as high as 2m/s. However, Zhai et al., (2015) argue that at that temperature (30°C) subjective thermal sensation remains in the neutral zone and with a fan it could be comparable to the thermal conditions of the subjects without fans at 26°C. Building bioclimatic chart adopted by Givoni (1998) reports that the upper- temperature boundary could be up to 3K more in a little breeze condition with air speed of 2m/s compared to the still air condition with an airspeed less than 0.25m/s. This means that the rising of air velocity can extend people's comfort zone.

Having observed the importance of increased air velocities to thermal comfort especially at high temperatures, researchers, such as (Zhang et al., 2007), went further to suggest recognizing an increase in air velocity as one of the actions to enhance thermal comfort. The airspeed limit was extended to 0.8m/s (160fps) by ASHRAE for operative above 25.5°C (77.9°F) in all types of buildings (Cândido et al., 2011). Further research based on numerous reports from fieldwork, convinced ASHRAE to vary the airspeed from 0.2m/s to 1.2m/s, and for higher activity levels over 1.3met there is no limit (Nicol et al., 2012). Elevations allowed in comfort limits are 1.2°C, 1.8°C, and 2.2°C for airspeeds of 0.6m /s, 0.9m /s, 1.2m /s respectively (Mishra and Ramgopal, 2015). This limit for airspeed level is based on the operative temperature and also on the difference between the mean radiant temperature and air temperature, and this limit of air speed level is based on the operative temperature (Toftum, Zhou, and Melikov, 2000). With the building occupant not having control over their environment, the limit goes back to Fanger's laboratory-based limits for draft in which the air velocity value must not exceed 0.2m/s.

Also, some thermal comfort researchers have advocated for the allowance of higher air movement in buildings that have no individual control. For example, Cândido et al., (2010) posited that it is important to investigate other sources of effects of air movement in actual buildings, with or without individual control. Candido argued that air movement limits imposed by current standards come out with inherent energy penalties and may not be providing occupants with the indoor environment they prefer. However, the low range of air movement specified was recently removed from ANSI/ASHRAE 55 (Schiavon et al., 2017). The new ASHRAE comfort standard 55-2017 specifies an extension of summer comfort zone with elevated air movement up to 0.8m/s (without personal control) and 1.2m/s (with personal control) (Zhai et al., 2015). However, when the air movement in a room is so slight, it will be unnecessary to include air speed in thermal comfort assessment since natural convention prevails at the clothed surface of the body. (Humphreys et al., 2007).

Clearly, a specific airspeed has many possible physiological and subjective effects that range from a pleasant sense of coolness to an unpleasant sense of draft, depending on the condition of the indoor climate variables and the occupants' individual factors (Candido and Dear, 2012). However, designers of buildings located in the tropics should take advantage of the recent suggestion in ASHRAE standard, for higher air velocity consideration in the warmer climates, to produce sustainable designs that rely on the infiltration of more air into naturally ventilated buildings. Apart from the ultimate benefit of providing buildings that contribute a reduction of greenhouse gas emission and cheaper to maintain, it could also provide what Jørn Toftum, (2004) refers to as indoor environments that are stimulating and pleasurable to the occupants.

Apart from the evidence of the benefit of increased air velocity to enhance thermal comfort, there are also reports that link it to better health and academic performance. The study conducted by Bakó-Biró, Kochhar, Clements-Croome, Awbi, and Williams (2007) found a positive relationship between increased ventilation rates and higher alertness, better work mood, the tendency for less tiredness and increased attention among pupils in schools.

3. Methods

3.1. Study area

Imo State, Nigeria was chosen as a study area. Imo State has a warm and humid climate. Based on Koppen-Geiger climate classification the state is within the wet and dry zone. It is between latitude 4° 45′N, 7° 15′N, longitude 6° 50′E, and 7° 25′E, and has two seasons; the rainy season and the dry season. The state is characterized by a high surface air temperature thus, architects have a big challenge in designing buildings that will moderate the indoor thermal conditions. The wind speed in the warm and humid zone area is generally of low strength (Tammy Amasuomo and Oweikeye Amasuomo, 2016).

A primary school was selected from each of the three senatorial zones that made up Imo State. The schools as shown in Figure 1. All the surveyed classrooms were NV and none of them had any air-conditioning system or fan. The selected classrooms had children within the age range of 7 to 12 years. The number of occupants in each classroom ranged between 25 to 30. Approximately 7060 copies of questionnaires and numerous environmental data were collected from 350 schoolchildren, who were repeatedly surveyed twice a day in two seasons.

Tinytag Ultra 2 (TGU-4500) was used to record the indoor temperature and indoor relative humidity (RH), while Tinytag plus 2 (TGP-4500) Gemini loggers measured the corresponding outdoor air temperature of the immediate outdoor environment of the indoor spaces being monitored. The outside data logger was well sheltered, avoiding direct sunlight and rainfall. The instruments used for the survey were of high quality as recommended by international bodies such as American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) and International Standard Organization (ISO). Kestrel 3000 Pocket Wind Meter was used to measure the indoor air velocity. Data collected with these instruments were exported to Excel spreadsheet, organised and statistically analysed into tabulation and regression graphs.

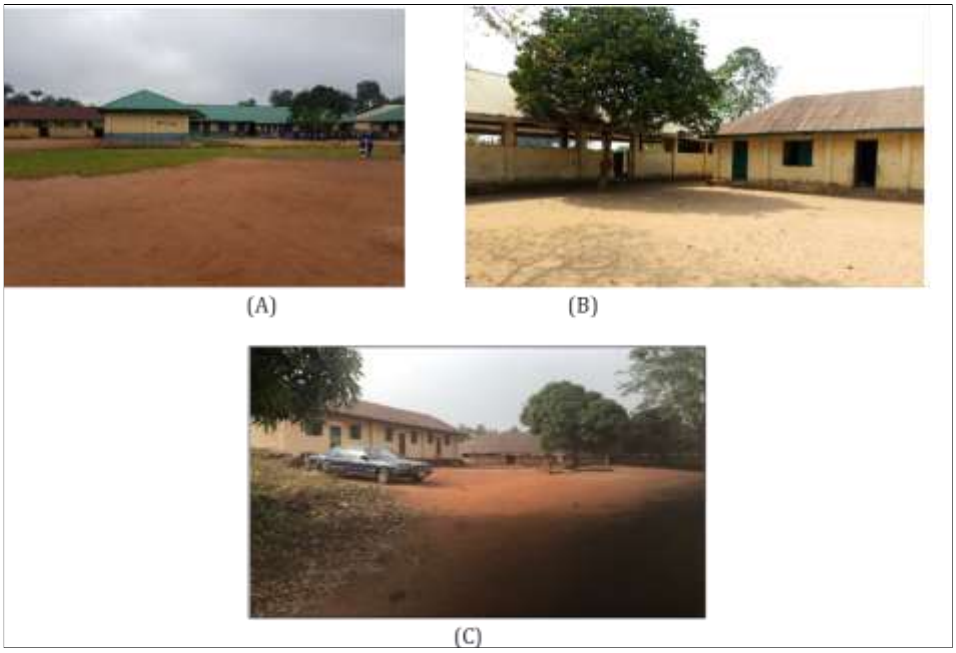

Figure 1 View of the school buildings

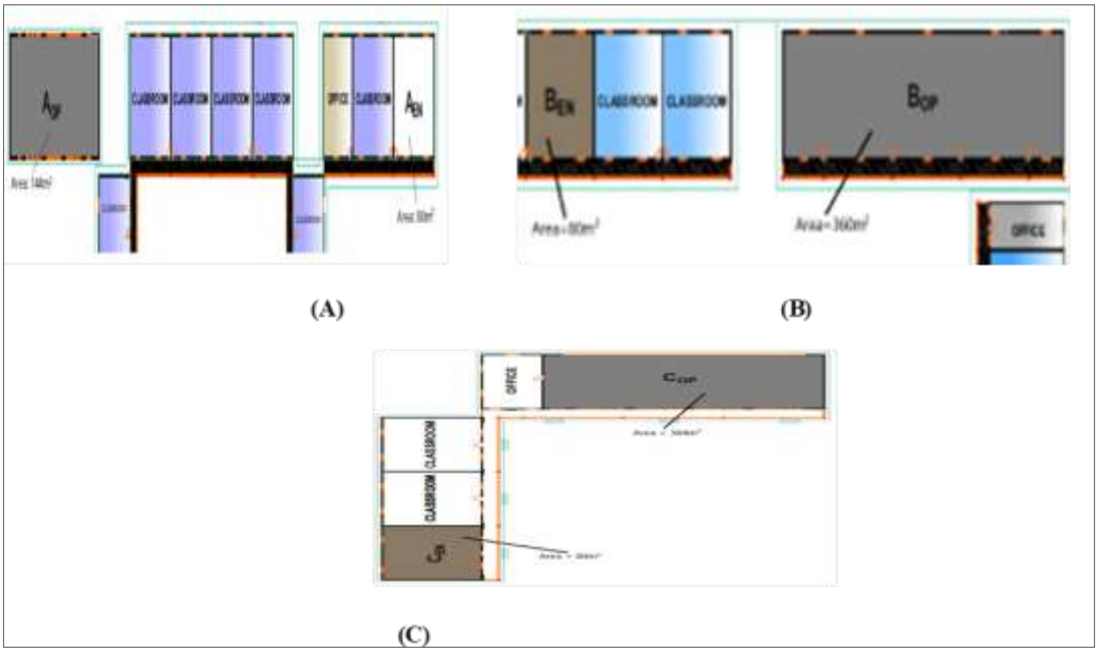

Figure 2 Floor plans of school buildings

Figure 3 Tinytag Ultra 2 (TGU-4500) and Tinytag Plus 2 (TGP-4017)

Table 1 Technical details of the measuring instruments

Instrument and Make	Measured parameter	Range	Resolution	Accuracy
Tinytag ultra 2 (TGU-4500) logger	Indoor air temperature	-25 to +85°C	±0.01°C	±0.3%
	Indoor relative humidity	0% to 100%	±0.3%.	±1.8% RH
Tinytag Plus 2 (TGP-4017) loggers	Outdoor Temperature	25 to +85 °C	±0.01°C	-
Kestrel 3000 Pocket wind meter	Air velocity	0.30 to 40.0m/s	-	±1.66%

3.2. Determining Classroom's Compliance with ASHRAE Standard 55

The adaptive thermal comfort model is based on the relationship between the indoor temperature and the outdoor temperature. Adaptive model suggests that these two variables mostly determine the comfort temperature of building occupants. Indoor air movement is another variable that can influence the thermal performance of a building. ASHRAE Standard 55 sets 80% and 90% acceptable comfort ranges of indoor spaces based on these variables (ASHRAE, 2017).

To determine the thermal performance in each of the surveyed classrooms, the prevailing mean outdoor temperature (T_{out}) of each classroom space was plotted against the corresponding daily mean indoor operative temperature (T_{OP}) putting into consideration the prevailing mean indoor air velocity. The result was compared with the 80% and 90% acceptable comfort ranges of the ASHRAE Standard 55-2017 (ASHRAE, 2017). The ASHRAE Thermal Comfort Tool is permitted to be used to ensure compliance (ASHRAE, 2017). Some other researchers who used the Centre for the Built Environment Thermal Comfort Tool to ensure compliance to the standard are (Hoyt, Schiavon, Piccioli, Moon, and Steinfeld, 2013 and Efeoma, 2017). Where the classroom under investigation does not comply with the requirements of the standard, the variables are further analysed using the Centre for Built Environment (CBE) thermal comfort tool. ASHRAE Standards 55 allows the use of a CBE thermal comfort tool to enhance thermal comfort by increasing airflow to more than 0.3m/s provided that the mean outdoor temperature in the space does not exceed 33.5°C (ASHRAE, 2017). For this study, the mean outdoor temperature in the surveyed classrooms did not exceed 33.5°C (Tables 5.2 and 5.4).

4. Results

4.1. School A

4.1.1. Classroom A_{OP}

Rainy Season: The prevailing mean indoor operative temperatures were plotted against the corresponding mean outdoor temperatures obtained from the field work. Each point represents one measurement carried out during the survey. The result is overlaid with the adaptive model of ASHRAE Standard 55. These can be compared with the 80% and 90% acceptable comfort ranges on the ASHRAE 55 adaptive comfort model (Hoyt et al., 2013). The result indicated that all the points were within the 80% comfort range and almost all the points falling within the 90% comfort range. Thus, classroom A_{OP} complied with the ASHRAE Standard 55 adaptive comfort standard with 28.6°C as the mean indoor operative temperature and 29.2°C as the mean outdoor temperature. Because of the compliance, no further analysis was needed. Figure 4 shows the mean indoor operative temperature plotted against the prevailing mean outdoor temperature.

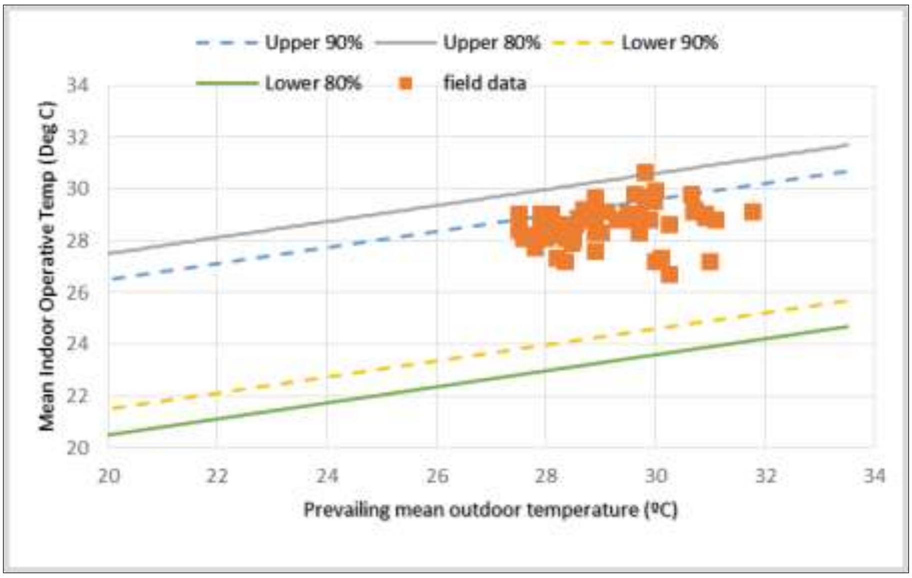

Figure 4 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

- *Dry Season:* However, during the dry season, in the same classroom, some of the points were outside the 80% and 90% adaptive comfort range as shown in Figure 5 at the mean indoor operative temperature of 29.4°C, mean outdoor temperature with value 29.6°C and at the prevailing indoor air velocity. The thermal condition in the classroom in this season was further analysed to determine its compliance with the ASHRAE Standard, by increasing the indoor air velocity using the CBE comfort analysis tool. By increasing the air velocity to 0.3m/s, the classroom complied with the ASHRAE Standard 55 adaptive standard as shown in Figure 6.

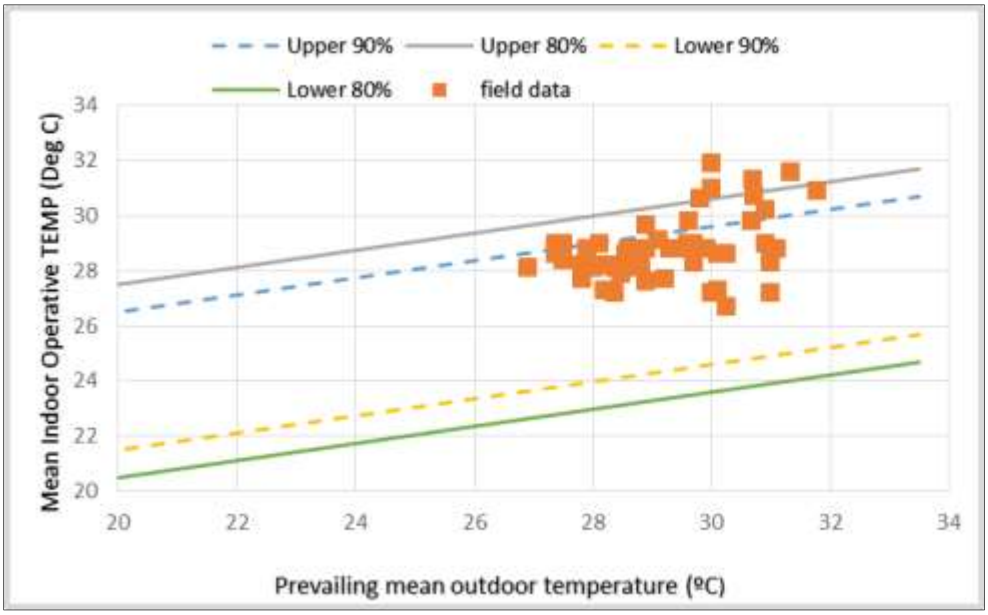

Figure 4 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

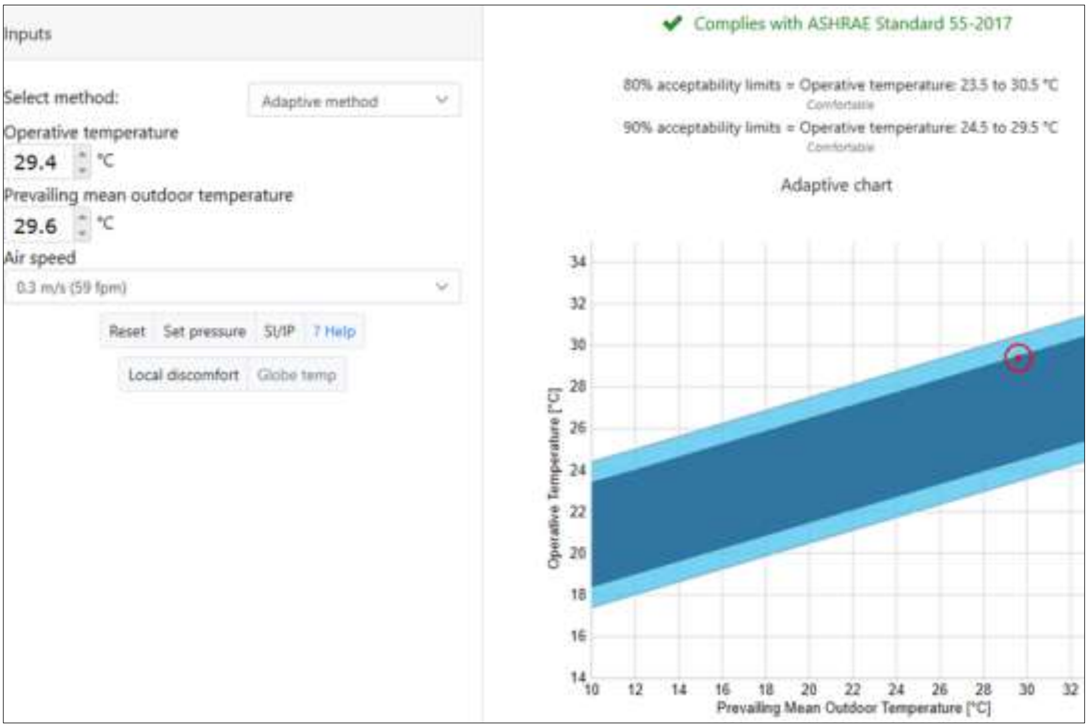

Figure 6 Analysis of classroom A_{OP} with air velocity of 0.3m/s using CBE Thermal Comfort Tool

4.2. Classroom AEN

- *Rainy Season*: Results of the measured indoor OT were plotted upon the corresponding outdoor temperature and compared with ASHRAE adaptive standard 55 as shown in Figure 7. Results indicated that almost all the points were within the 80% and 90% range of the standard with a mean indoor operative temperature of 28.7°C and the corresponding mean outdoor temperature of 29.2°C. This suggested that classroom A_{EN} in the rainy season complied with the requirement of the standard. As a result, there was no need for further analysis.

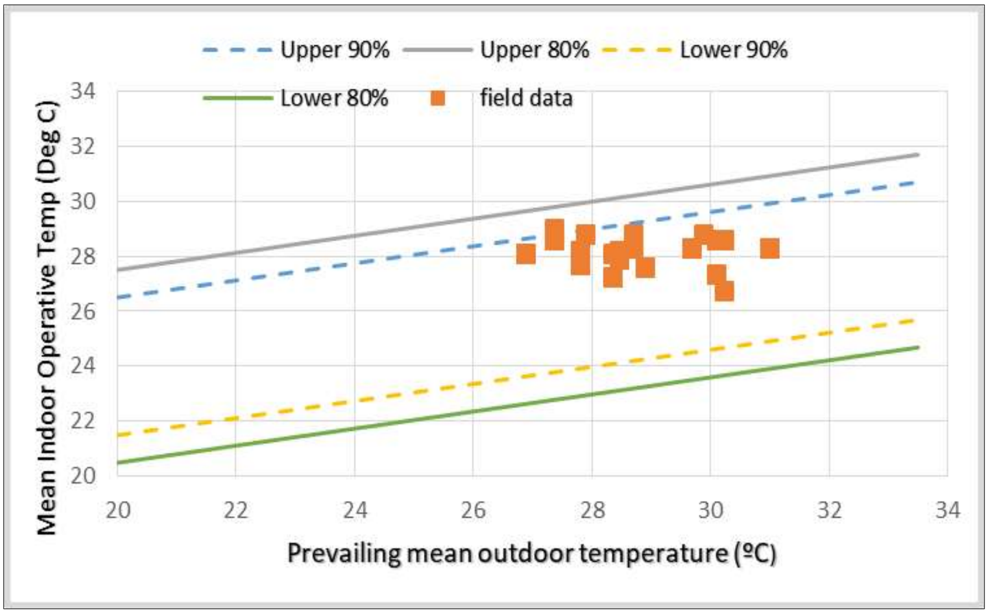

Figure 7 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

- *Dry Season*: However, during the dry season survey, some of the points were outside the 80% comfort range as shown in Figure 8 This indicated some discomfort in the classroom during the dry season at a mean OT of 29.5°C with 29.6°C as the mean outdoor temperature. The thermal condition in the classroom during the dry season was further analysed using the Centre for the Built Environment thermal comfort analysis tool by increasing the air velocity beyond the one recorded during the survey. As shown in Figure 9, with a higher air velocity of 0.3m/s the classroom complied with the Standard, based on 80% acceptability only. According to the CBE comfort tool, with 90% acceptability, the users of the classroom space would feel very warm even at a higher air velocity of 0.3m/s. However, the users of the indoor space can only be comfortable at air velocity of 0.6m/s for the 90% acceptability as shown in Figure 10.

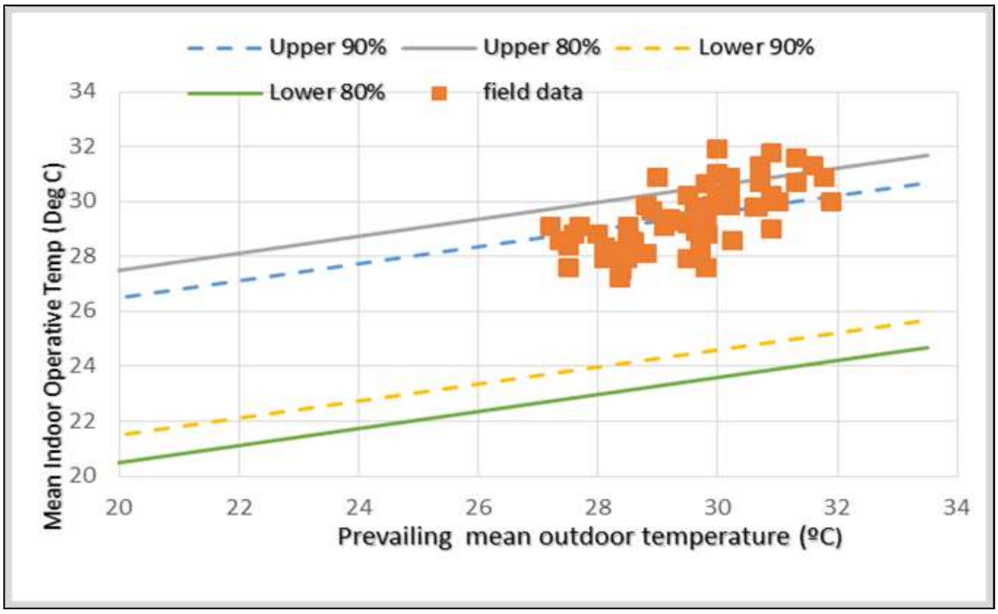

Figure 8 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

Figure 9 Analysis of classroom A_{EN} with air velocity of 0.3m/s using CBE Thermal Comfort Tool.

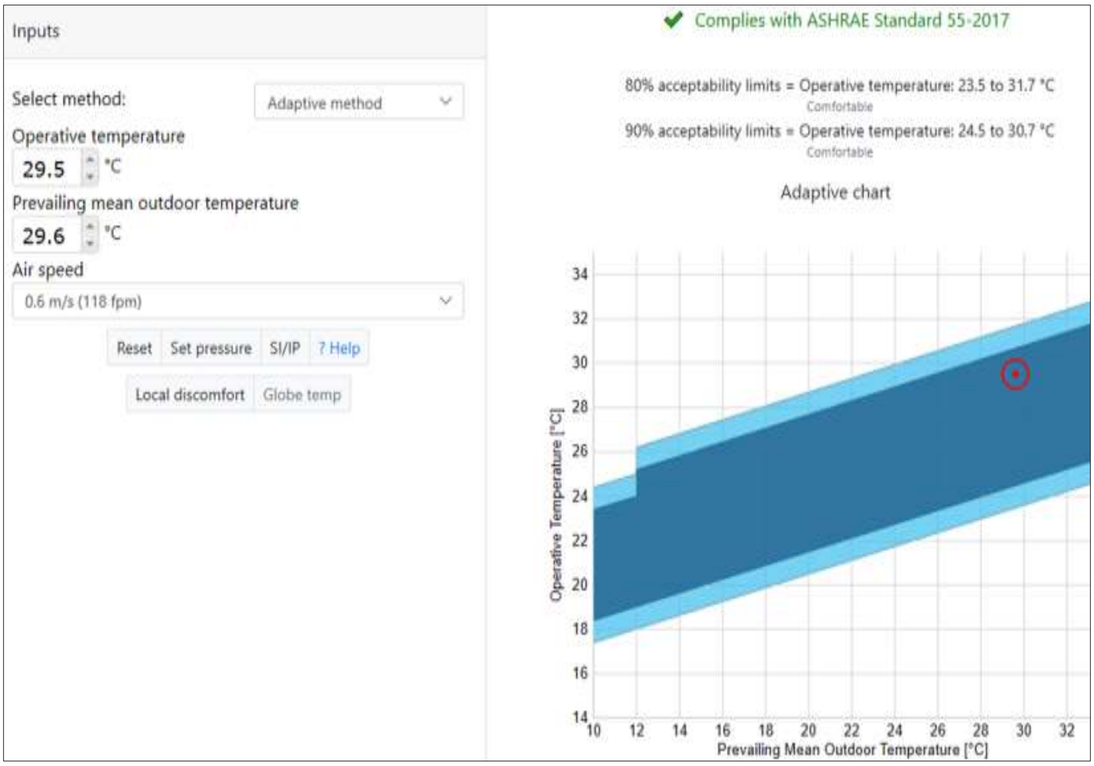

Figure 10 Analysis of classroom A_{EN} with air velocity of 0.6m/s using CBE Thermal Comfort Tool

4.3. School B

4.3.1. Classroom BOP

- *Rainy Season*: Figure 11 shows the result of the regression of the mean indoor operative temperature against the mean outdoor temperature in classroom B_{OP} in the rainy season. The classroom complied with the standard at the mean indoor operative temperature and mean outdoor temperature of 28.2^{o}C and 28.6^{o}C, respectively considering both 80% and 90% acceptability criteria.

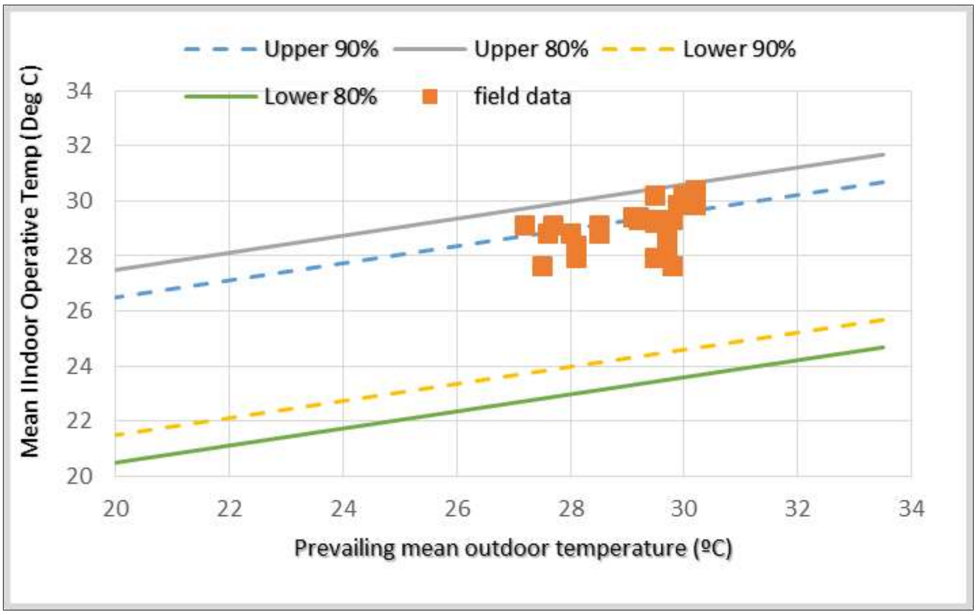

Figure 11 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

- *Dry Season:* Figure 12 shows the result of the regression of the mean indoor operative temperature against the mean outdoor temperature in classroom B_{OP} in the dry season survey. The votes were within the 80% and almost all the points were within the 90% acceptability criteria at a mean indoor OT of 28.9^{o}C with mean outdoor temperature of 29.1°C. There was no need for further analysis.

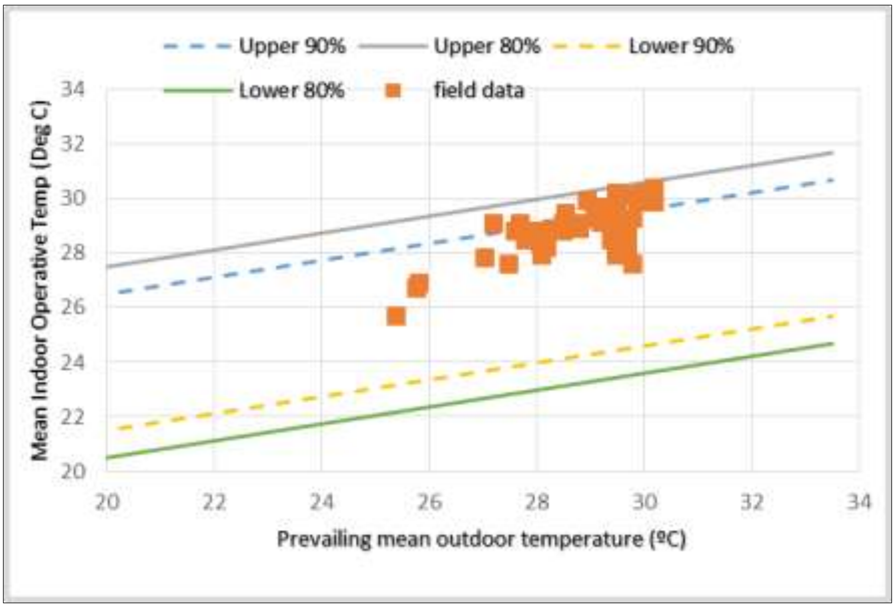

Figure 12 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

4.3.2. Classroom B_{EN}

- *Rainy Season:* Figure 13 shows the result of the regression of the mean indoor operative temperature against the mean outdoor temperature in classroom B_{EN} in the rainy season survey. The votes were within the 80% and 90% acceptability criterion at a mean indoor OT of 28.3°C with mean outdoor temperature of 28.6°C.

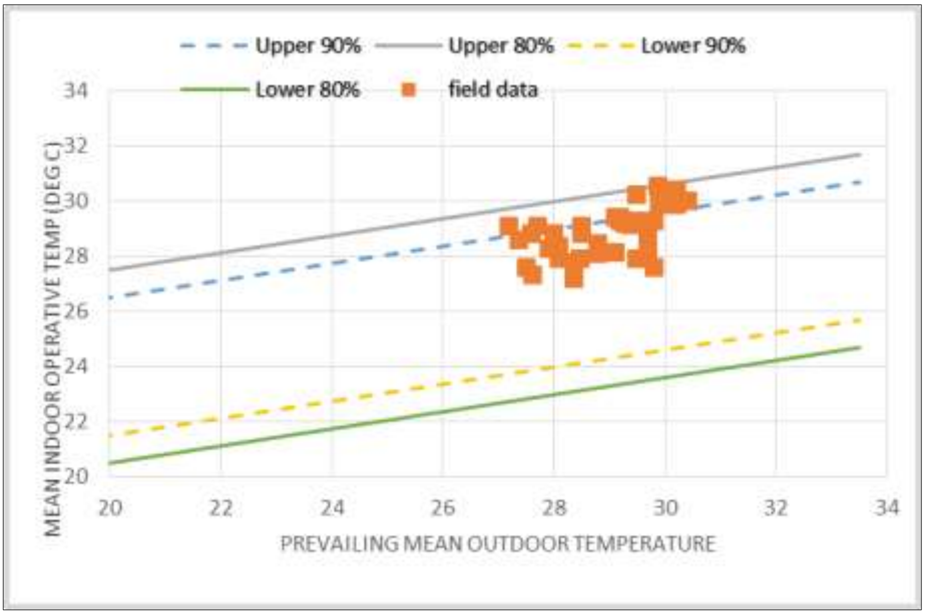

Figure 13 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

- *Dry Season:* Figure 14 shows the result of the regression of the mean indoor operative temperature against the mean outdoor temperature in classroom B_{EN} in the dry season. The votes were within the 80% and the 90% acceptability criteria. Thus, the classroom complied with the standard at a mean indoor OT of 28.9°C with mean outdoor temperature of 29.1°C

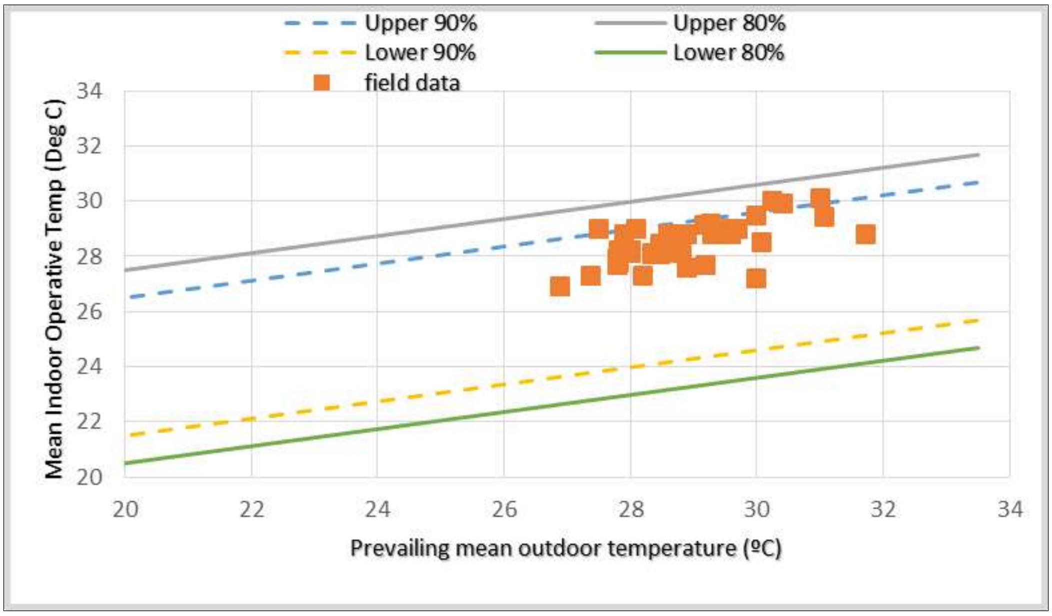

Figure 14 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

4.4. School C

4.4.1. Classroom C_{OP}

- *Rainy Season*: As seen in Figure 15, with the indoor mean temperature of 28.7°C and outdoor mean temperature of 29.4°C, the points were within the 80% comfort zone. However, the very few points that tended towards the periphery of the 80% comfort zone were further analysed using comfort tool by assuming a higher air velocity of 0.3m/s (Figure 16). At this increased air velocity, the classroom complied with both the 80% and 90% acceptability range.

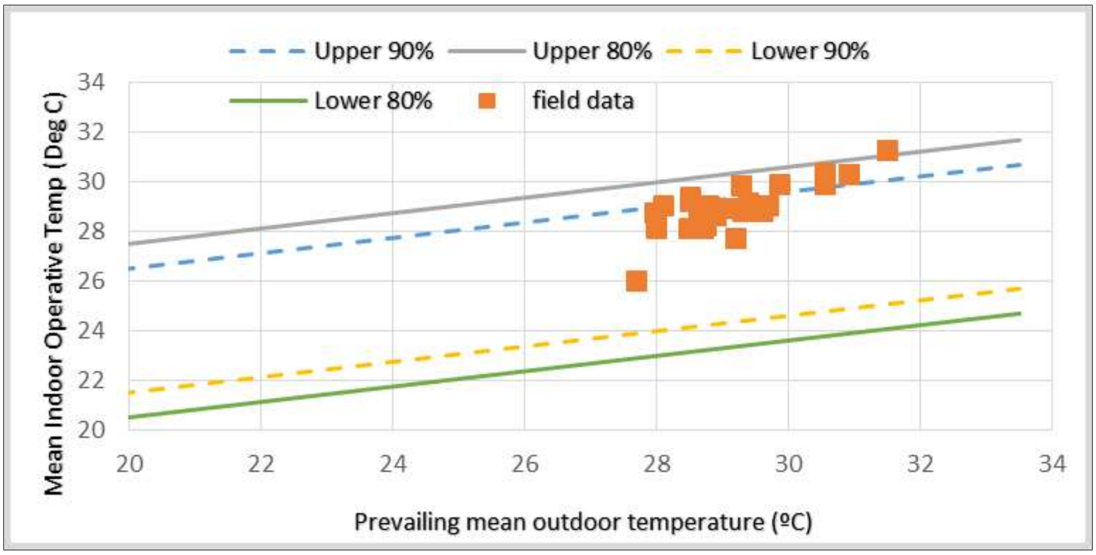

Figure 15 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

Figure 16 Analysis of classroom C_{OP} with air velocity of 0.3m/s using CBE Thermal Comfort Tool

- *Dry Season:* As seen in Figure 17, with the indoor mean temperature of 28.8°C and outdoor mean temperature of 29.1°C, the points were within the 80% comfort zone. Though, some few points tended towards the periphery of the 90% comfort zone however this classroom was deemed to have complied with the ASHRAE standard 55.

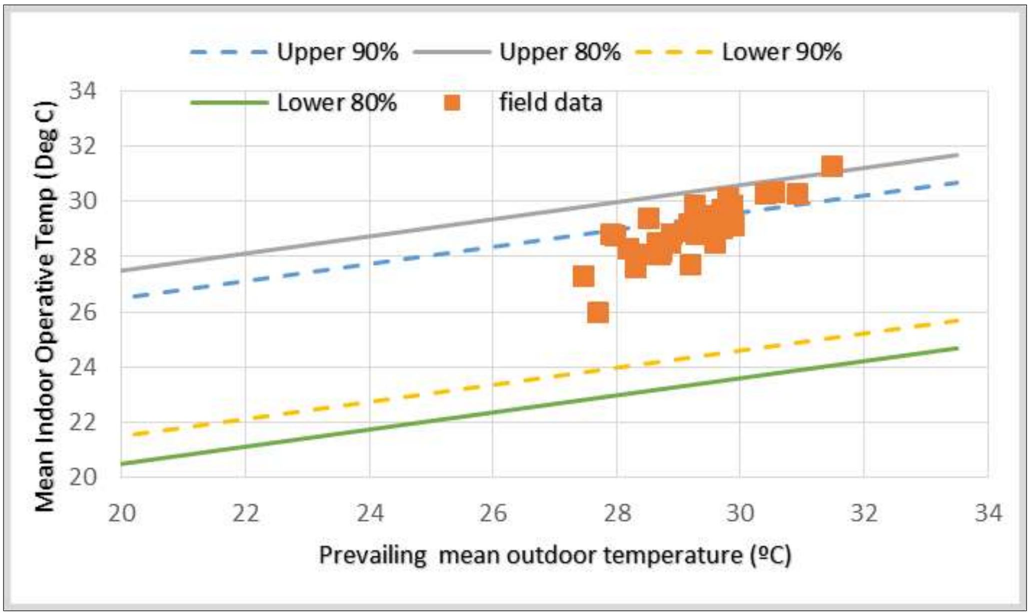

Figure 17 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

4.4.2. Classroom CEN

- *Rainy Season:* As seen in Figure 18, with the indoor mean temperature of 29.2^{o}C and outdoor mean temperature of 29.4^{o}C, the points were within the 80% comfort zone. However, the very few points that tended towards the periphery of the 80 % and 90% comfort zones were further analysed using comfort tool by assuming a higher air velocity of 0.3m/s (Figure 19). With this, the points were within the 80% and 90% criteria

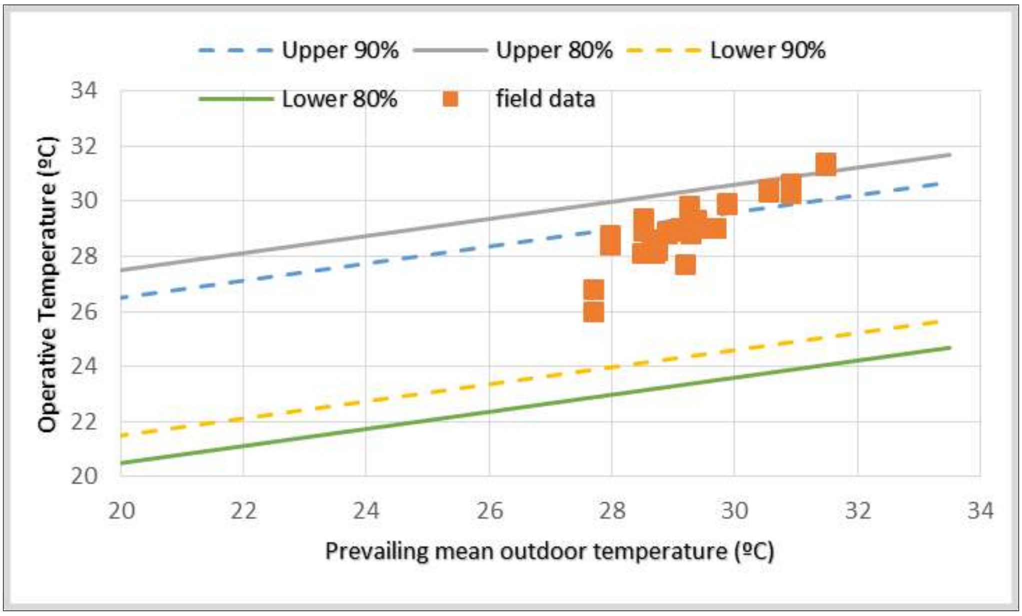

Figure 18 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

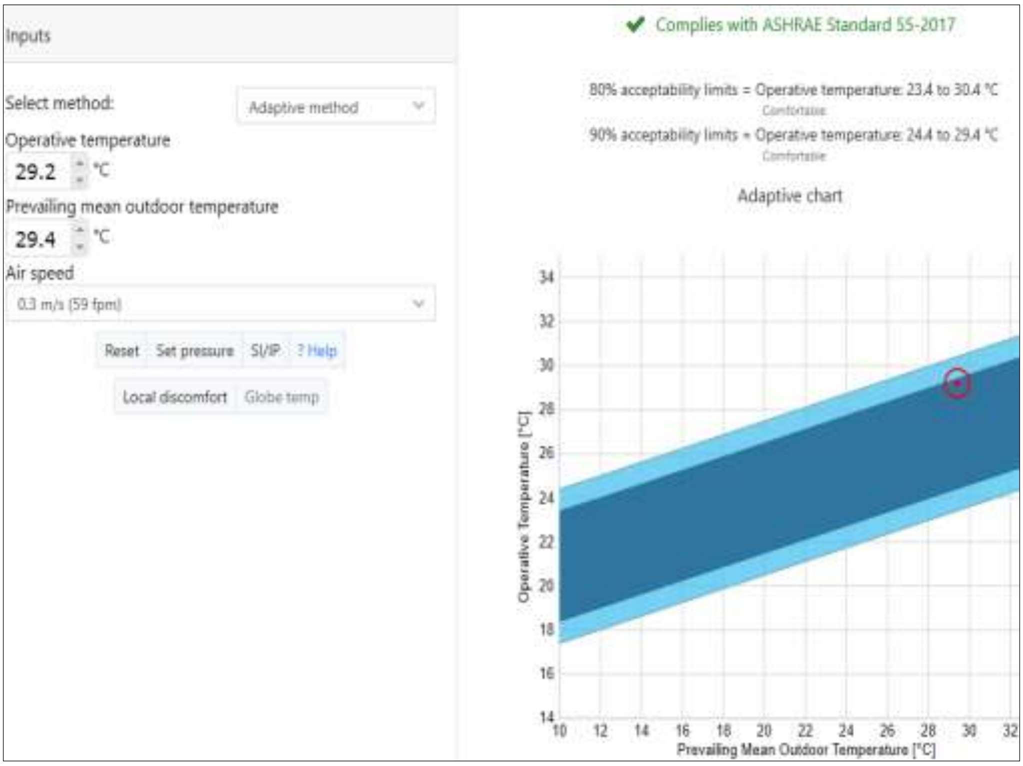

Figure 19 Analysis of classroom C_{EN} with air velocity of 0.3m/s using CBE Thermal Comfort Tool

- *Dry Season*: As seen in Figure 20, with the indoor mean temperature of 29.0°C and outdoor mean temperature of 29.1°C, the points were within the 80% comfort zone. However, the very few points that tended toward the periphery of both the 80% and 90% comfort zones were further analysed using comfort tool by assuming a higher air velocity of 0.3m/s (Figure 21). With this increase the classroom complied.

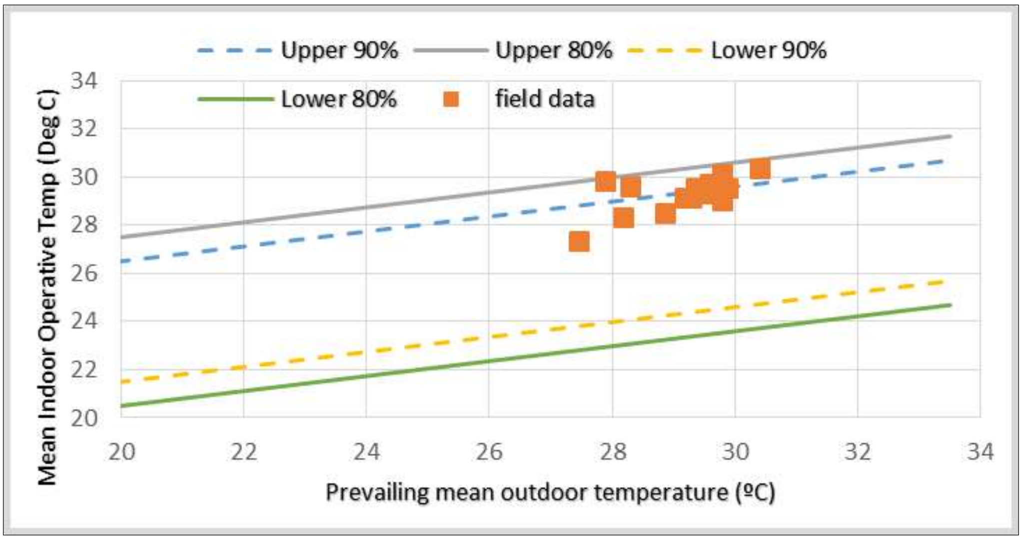

Figure 20 Mean indoor T_{OP} plotted against the prevailing mean T_{out}

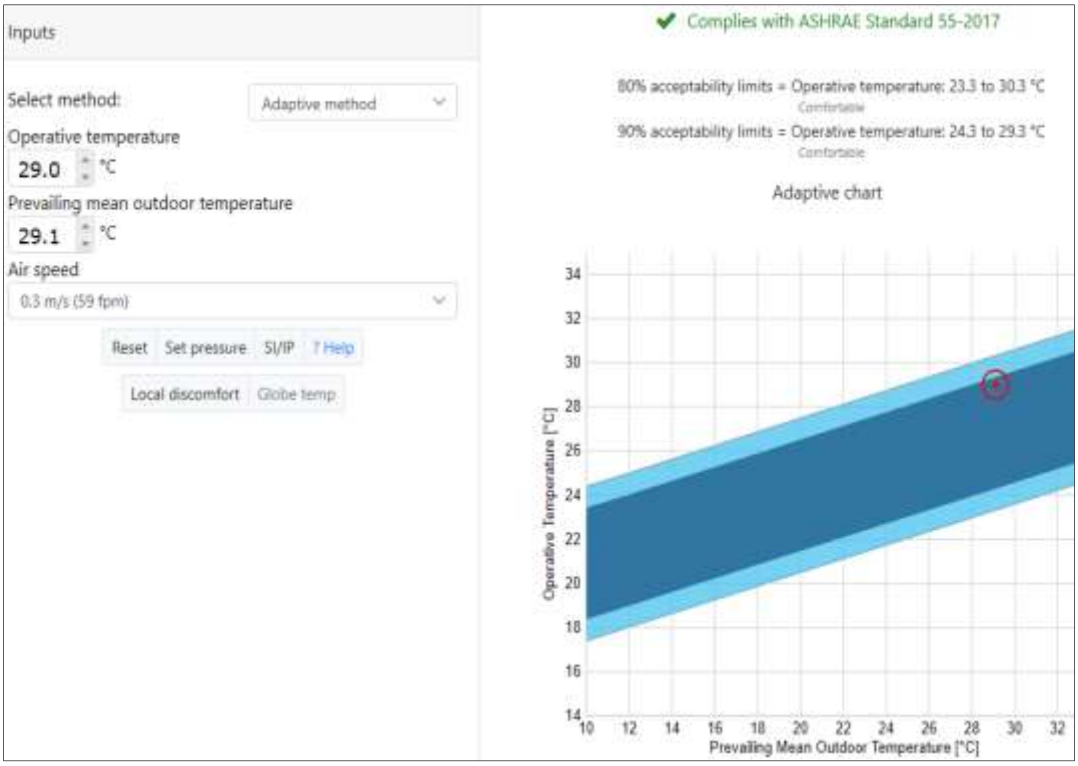

Figure 21 Analysis of classroom C_{EN} with air velocity of 0.3m/s using CBE Thermal Comfort Tool

5. Conclusion

This work examined the influence of air velocity on the comfort of building occupants in the tropics with southeast Nigeria as a case study. Results have shown that building occupants are thermally comfortable at higher air velocity in the temperature range between 26-31^{o}C. There is a need for the provision of adequate building openings in buildings located in the tropics.

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