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EFFECTS OF ENVIRONMENTAL GEOMETRY ON WINDFLOW FOR ACTIVATING NATURAL VENTILATION IN BUILDINGS

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Abstract:
Natural ventilation is hugely reliant on microclimatic conditions of an environment. In urban setting, this is often influenced by wind movements and air temperatures. The correlation between building heights and their proximity to each other and presence of physical structures that form the urban geometric elements are known to influence the incoming and outgoing wind speeds. This in turn impacts on the quantity and quality of air available for wind driven natural or hybrid ventilation. In this paper, field study was carried out on selected building and its immediate surroundings within Baze University Campus in Nigeria. This study aims to identify and evaluate the behaviors of air flow as well as analyze the impacts of environmental geometric elements on the natural ventilation potential within the environment. For this purpose, a field survey was conducted on a non-rainy day in November 2025 during the peak class periods of the day (10am to 4pm), in order to generate indoor and outdoor temperature and wind velocity data using Infra-red Sensor-type temperature and air flow monitoring equipment. The study utilized both observatory analysis and CFD simulation to analyze and synthesize the findings. The result showed a decreased wind velocity closer to the building walls, due to obstructions caused by the presence of trees in close proximity to the buildings. The general conclusion is that the surrounding street elements like trees and landscaping structures prevail in the diversion and consequent reduction of wind speed needed for natural indoor ventilation.
Keywords: ***Airflow patterns, Environmental geometry, Natural ventilation, Passive ventilation, Street geometry, Urban geometry***

1. INTRODUCTION

Buildings in educational facilities are indispensable in providing favorable environments for teaching and learning. Due to this, classrooms spaces should possess enabling conditions that enhances student concentration thence, improving the general learning process. On the other hand, the effects of the rise in global temperatures and urban heat islands in cities constantly elevate the thermal challenges for educational and associated buildings within urban centers (Rani, 2024). The built environments in these tropical urban settings are persistently exposed to solar radiation, which in turn elevates temperature and relative humidity conditions (Vasileios, 2020). These conditions contribute to the increases of the peak cooling and electricity loads required for building spaces (Vasileios, 2020, Lefevre, 2025). Studies show that thermal comfort in classroom and educational spaces are directly linked to students well-being and productivity (Zomorodian, 2016). Since a relationship is struck between the learning process and the affiliated environment, the designs of these educational spaces and its associated environments must optimize sustainable options which take into cognizance the local microclimates (Dinić Branković et. al, 2025). Local microclimates are often defined as the distinctive climate of a small-scale area which may be a street, park, or part of a city. The area often exists within atmospheric boundary layers and upper soil regions. In terms of size, a typical space-scale of about 100m^2 can be used to define a microclimatic zone and they often comprise of local landscape elements (Barry, 2016). The geometry of an urban microclimate zone is known to impact on the outdoor and indoor environments relative to components like:

i. Solar access (inside and outside the buildings),
ii. Permeability to airflow required for the urban and building ventilation,

iii. The potential for cooling of entire urban system.

A typical urban microclimatic zone comprises of stationary and moving elements that form barriers which collectively define the flow pattern of wind within urban districts. The presence of these barrier elements (obstacles) like buildings, street furniture, trees etc. are frequently obstructing the air flow within the boundary layers of urban districts as seen in figure 1. The results are the gentler airflow and wind pressures observed within the urban canopy layer (Okeil, 2010). Therefore, understanding the airflow patterns, orientation and wind speed in urban districts within the tropical regions is essential for evaluating the potentials of natural ventilation

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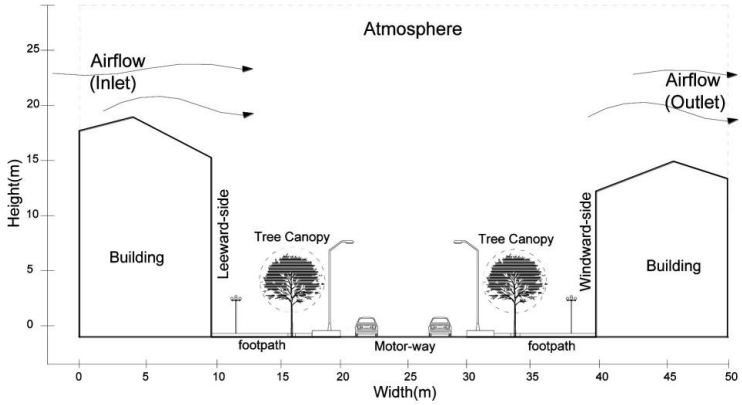


Figure 1. Urban street composition with the barrier elements (trees, cars and landscape components) that influence airflow conditions in the urban canopy layer

Study reveals that climate-responsive educational buildings are considered critical in providing conducive environment for teaching and learning (Wu et al., 2025). Owing to this, classrooms and learning spaces should be designed to improve student concentration and interactivity, thus elevating the overall learning process (Akubue et al., 2025). Thermal comfort in educational buildings is directly related to student's productivity, health, and energy efficiency (Zomorodian, 2016). Two major factors are typically regarded as responsible for the thermal comfort environmental, these includes environmental and personal factors. While Environmental the factors refer to the air temperature, relative humidity, airspeed and radiant temperature, the personal factors refer to clothing insulation and human metabolic rate (ASHRAE, 2020). Thermal comfort studies often utilize adaptive models in naturally ventilated spaces, while using rational models for air-conditioned spaces in defining satisfactory indoor comfort conditions (Lamberti, 2020). The adaptive model is recognized as more acceptable for tropical climates owing to the major reliance on naturally conditioned spaces, coupled with the facts that students can adapt to these temperature ranges (Abreu-Harbich et. al, 2018). Furthermore, adaptive models relate the indoor temperatures that are only valid in naturally conditioned spaces or for outdoor temperature which range between the values of 10℃ to 33.5℃ (ASHRAE, 2013).

A study of thermal comfort in naturally ventilated classrooms of a secondary school within Abuja was conducted during the periods of March (when average daily temperature highs exceeded 32℃). This study was conducted for the purpose of confirming the applicability of ASHRAE Standard 55 in hot and dry climates (Mustapha, 2023). The study however identified that almost half of the students studied felt comfortable even at higher temperatures than the ones indicated by the ASHRAE Standard 55 (up to 3.1℃ higher). This thus suggests a wider comfort-temperature range for classrooms that are naturally ventilated in locations like Abuja and similar climatic regions. Abuja city is also known to experience moderate heat stress from the months of June to November (Musari, 2015). This observation

further buttresses the need for environmental and thermal comfort studies in all educational buildings within Abuja owing to the fact that students normally spend considerable amount of time within the classroom environment (Omali, 2020). While thermal sensation may be attributed to the human body's thermal balance, environmental parameters such as air movement and thermal environment conditions (like the environmental geometry) play significant roles on the ultimate thermal sensation (Baruah, 2014). With respects to air movement, study shows that natural wind driven ventilation is considered as a sustainable alternative to the mechanical ventilation options in maintaining thermally comfortable and healthy indoor environments (Angelopoulos, 2017). Furthermore, research revealed that effectiveness of natural ventilation is best evaluated using fluid dynamics (CFD) analysis elements such as air flow patterns, airflow rates, pressure distributions and average velocities. This evaluation system not only applies to assessing the performance of natural ventilation, but also in understanding the general indoor and outdoor environmental conditions (Alabi, 2024). Through the reviews of related literature on conditions of climate-responsive educational buildings within Nigeria, it is evident that the role of urban geometrical barriers is excluded in the wind flow analysis for natural ventilation. This observation further buttresses the need for a study that relates the environmental and thermal comfort conditions in all educational buildings within Abuja to the nature of external landscaping elements which may impact on the general outdoor and indoor classroom environment.

2. STUDY AREA

This study is conducted within the Baze university campus in Abuja, Nigeria. Abuja lies between latitudes 8°25'N and 9°25'N and longitude 6°45'E and 7°45'E (Figure 2). The city lies at an altitude of 840m above mean sea level and is estimated to have a population that is under one million residents (Isioye, 2020).

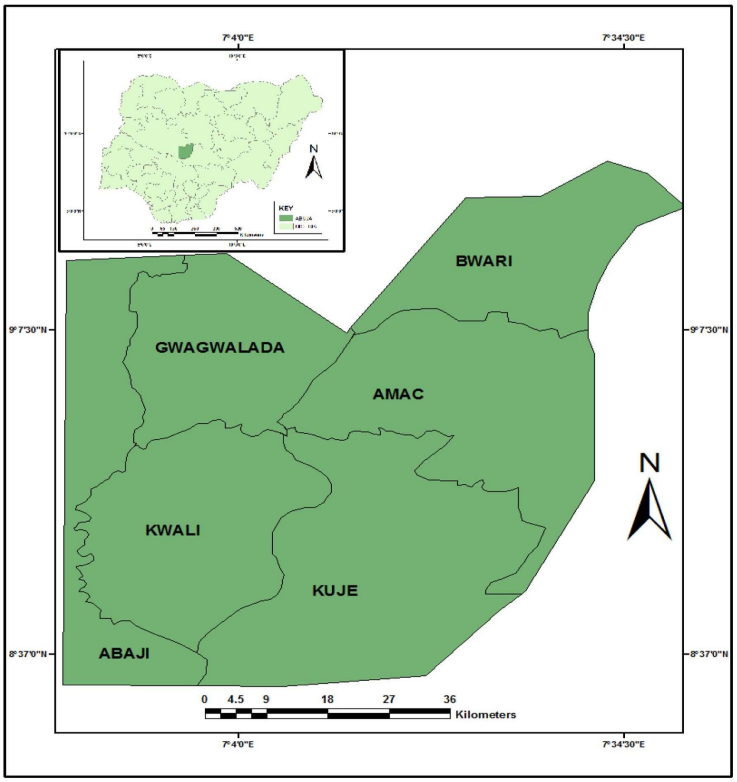


Figure 2. Map of Abuja the central capital city of Nigeria
Source: National Space Research Development Agency (NARSDA)

2.1. ABUJA CLIMATIC CONDITIONS

The climate classification by Koppen did describe the climate of Abuja as a tropical wet and dry with two distinctive weather conditions, which comprise of the Warm humid rainy seasons and the Very hot dry seasons (Kottek et. al, 2006). In between the two distinct seasons experienced in Abuja is the Harmattan season which is characterised by cooler, foggy and dry conditions (Dorcas, 2020). While the warm humid seasons last through the months of April to November, the Harmattan season usually falls between December and February. The temperatures in Abuja city are generally high (except for the Harmattan periods), with values that range between 28 ℃ - 37 ℃ in the day times and between 18 ℃ - 23 ℃ at night times. According to the meteorological data on Abuja climate, March is designated as the month with the hottest temperature averaging up to 36.9 ℃, while the month of August represents the coldest month averaging up to 28.1 ℃. Also, while the hottest months of the year usually fall between the months of January and April with daytime temperature highs of about 35 ℃. The city of Abuja experiences about 200 to 320 hours of intense solar radiation monthly between the months of November to April. However, during the rainy months, it drops down to 250 hours and below owing to the abundance of cloud cover as shown in Table 2. With regards to precipitation, the rainy season commences from March and often continues till November with the peak rainfall periods occurring between the months of July and September (which accounts for more than half of the total annual rainfall). The most significant factor in the Abuja climate is the oppressive humidity, which falls between March and November (as seen in Table 1).

Table 1. A summary of Abuja city's climatic conditions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Avg. Temperature (°C)	27	28.6	29.6	28.6	26.5	24.5	23.4	22.9	23.6	24.7	26.4	26.7
Min. Temperature (°C)	20.5	22.3	23.8	24 °C	23 °C	21.7	20.9	20.7	20.8	21.3	21.1	20.4
Max. Temperature (°C)	33.6	34.9	35.5	33.8	30.6	28.2	26.8	26.2	27.6	29.1	32 °C	33.2
Precipitation / Rainfall (mm)	2	6	20	57	138	205	269	326	290	144	11	1
Relative Humidity (%)	26%	29%	38%	57%	73%	82%	85%	87%	85%	80%	51%	29%
Rainy days (days)	1	1	3	7	14	17	21	21	20	15	2	0
Avg. Sun hours (hours)	10.3	10.3	10.0	8.3	6.1	4.5	4.3	3.9	4.6	6.3	9.8	10.3

Source: Climate-Data.Org

Table 2. Abuja city's mean monthly sunshine and daily daylight hours

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly sunshine hours	266	297	325	320	322	291	285	256	277	317	321	328
Mean daily daylight hours	11h 38m	11h 49m	12h 3m	12h 18m	12h 31m	12h 37m	12h 34m	12h 23m	12h 9m	11h 54m	11h 41m	11h 35m

Source: Climate-Data.Org

In the case of the yearly windy conditions within the Abuja climate as presented in Figure 3, the average hourly wind speeds experiences mild seasonal variation annually. While the windiest months fall between January to March with average wind speeds ranging from 6 to 11mph (i.e. 10 to 18 kmph), the calmest months fall between September to October with wind speeds of about 4 mph (i.e. 6.5 kmph). The meteorological data on Abuja's climate summarizes the windiest part of the year lasting for about 5 months (i.e. from the months of November to May), with average wind speeds ranging above 5.2mph (8 kmph). It also identifies

the windiest month in Abuja as January, with average hourly wind speeds of about 6.4mph (10 kmph). Data also shows that the overall seasonal changes are mostly driven by the dry and rainy periods, with slight increases in speed recorded during the driest season.

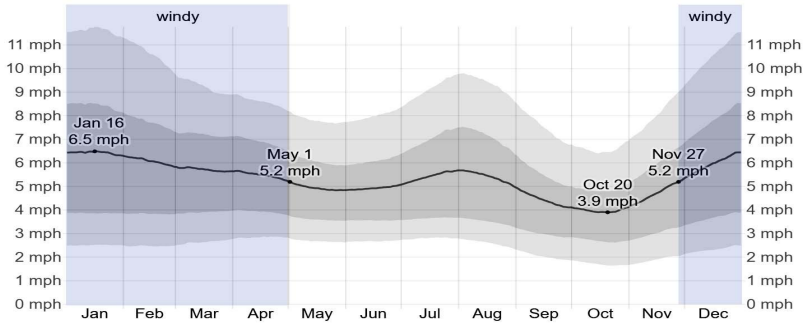


Figure 3. Average monthly wind speeds in Abuja
Source: Climate-Data.Org

2.2. SIGNIFICANT MICROCLIMATIC CONDITIONS AT BAZE UNIVERSITY, ABUJA

Baze university is located in the Abuja federal capital territory (FCT), off the Jabi-Airport road and near the Idu industrial district within Abuja Municipal Area Council (AMAC). The university campus is notable for its green landscaping, with the presence of Low-branching trees and foliage covers as seen in Figures 4, 5 & 6. The microclimate observed on the university grounds includes the building geometry, green spaces, ground and building surface materials. These elements are notable for their significant impact on the thermal and environmental comfort conditions as well as the airflow quality and patterns within the campus. These elements and their impacts are especially critical to the ambient conditions experienced within the different climatic seasons in Abuja. Factors like the street geometry and building layout, foliage and vegetation types (trees, grass), as well as solar radiation values all influence the magnitudes of temperature, humidity and wind conditions in this area (Segura-Barrero, R, 2022).

Figure 4. Aerial view of Baze University's Abuja Campus

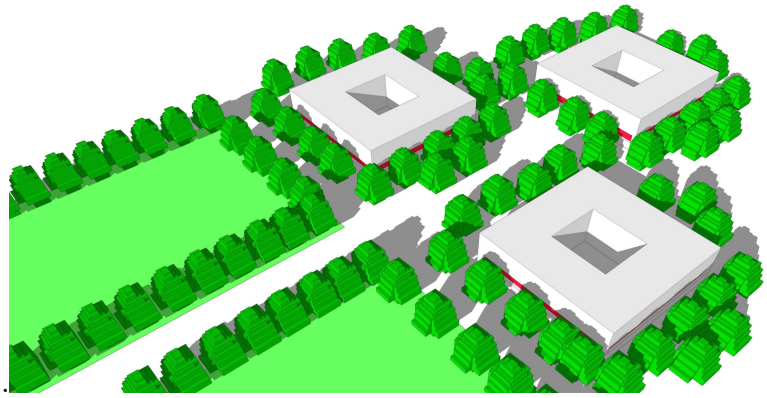
Figure 5. Closer view of typical academic building surrounded by Low-branching trees

Figure 6. Street View of a typical academic area at Baze university

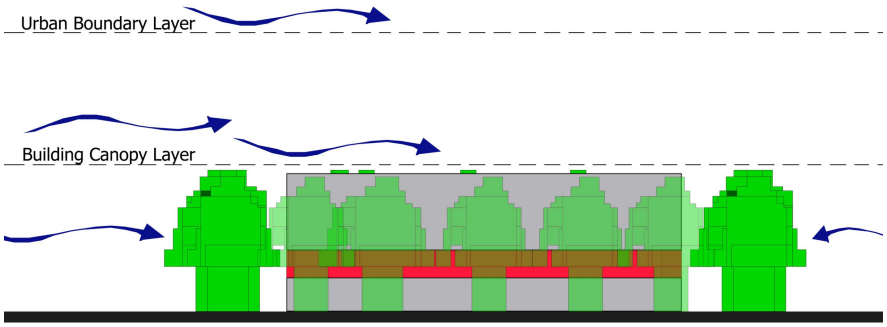
2.3. OVERVIEW OF BAZE UNIVERITY CAMPUS ENVIRONMENTAL GEOMETRY

As observed in 5 and 6, the campus environment in the study area is predominantly green, with the mix of low level buildings and trees in close proximity to each other, hence creating a sense of sub-urban scenic atmosphere. The environmental geometric setting that is revealed features a compact type configuration (between major components) with little or no spacing created between the building geometry and the plant geometry as illustrated in figure 7. While the existing Public Open Spaces (POS) like car parking areas and walkways enabled the attainment of ample spaciousness in the campus layout (which would have been an effective component of the configuration), the placement configuration between the buildings and plants remained unchanged in most cases, thus forming a general asymmetrical formation all round. This typical configuration of stationary elements forms the major obstacles that affect the flow of wind and are also believed to result in the gentler airflow observed within the building canopy layers in the campus settings.

This study intends to investigate this behavior as to ascertain the level of airflow energy reserved within the canopy layer which the buildings depend on for indoor wind driven ventilation purposes.



(a)



(b)

Figure 7(a). Aerial view, indicating the compact environmental geometry
Figure 7(b). Obstructed wind-flow in the Building canopy layer by plant geometry

3. MATHERIALS AND METHODS

This study aims at analyzing the airflow patterns and the influence induced by environmental obstacles within the urban space. The objective is to understand and be capable of predicting orientation of urban components in the design of layouts. For this purpose, this paper adopts an empirical research method which combines field observation and measurements of environment conditions within the study site as illustrated in the research framework (Figure 8). Data obtained from the field measurements are utilized in reviewing existing conditions and simulation analysis of airflow within the study environment.

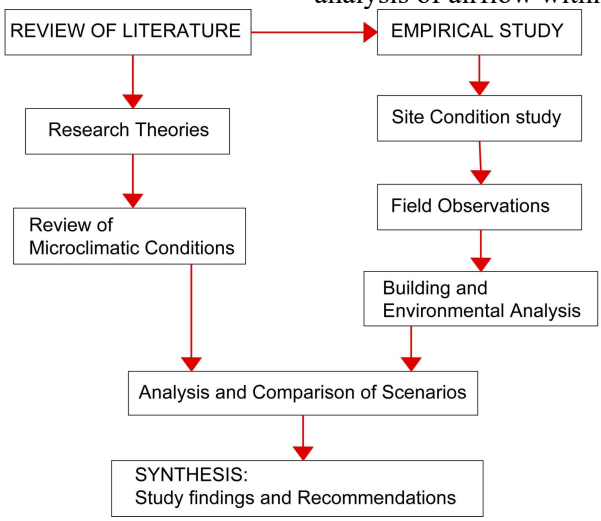


Figure 8. Research Framework

For this study, field observations were conducted on a typical windy day (November 8th 2025) within the selected study area represented in red (Figure 10). The measurements taken included dimensions of geometric structures, outdoor wind speeds within selected spots at heights of 2.1m (lower floor window levels), indoor wind speeds within the classrooms in the measurement zone and ambient air temperature at selected spots. The instruments employed for the climate related experimental measurements as shown in Figure 9 include:

a. 4 nos. of Raytek, (Raynger ST) Infra-red Sensor temperature monitoring equipment (measures air temperature, humidity)
b. 4 nos. of Thermo-anemometer (measures indoor and outdoor air movement/air velocity).

c. A laptop (computer) with the PHOENICS-VR application was used for Computational Fluid Dynamics (CFD) simulation and data collation during the study.

Raytek, (Raynger ST) Infra-red Sensor temperature monitoring equipment.	Temperature-Velocity-Humidity monitoring equipment

Figure 9. Climate and thermal Data equipment used in the field experiment measurements

Figure 10. Study area with indications of measuring points, seasonal wind paths and obstructive geometry (trees)

The field survey was conducted within a six hour period of the day (10:00am - 4:00pm), on a non-rainy day in November. This 6 hour period connotes the peak academic periods of the day at Baze University. The measurements taken provided the following Primary data:

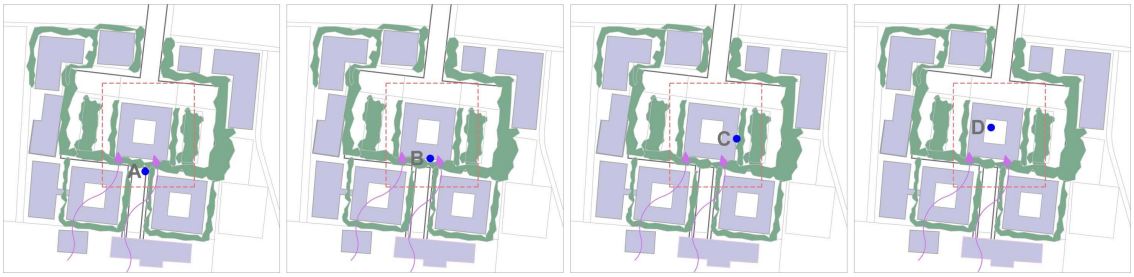
a. Distances of vegetation geometry (tree clusters) to the Building in the study area,
b. External Air velocity readings at points A,B,C&D,
c. Internal Air velocity readings within 2 classrooms (X & Y) facing the seasonal wind direction (SW).

The data collected from this study were subjected to a descriptive analysis by relating them to the environmental conditions using graphical analysis as to ascertain the values of each area against others. Also these data was utilized in the modeling of existing conditions for the purposes of simulation and analysis of airflow within the external and classroom environments using PHOENICS-VR CFD tool. The results gotten are analyzed using graphical means in combination with comparative and descriptive analysis.

4. ANALYSIS OF AIRFLOW

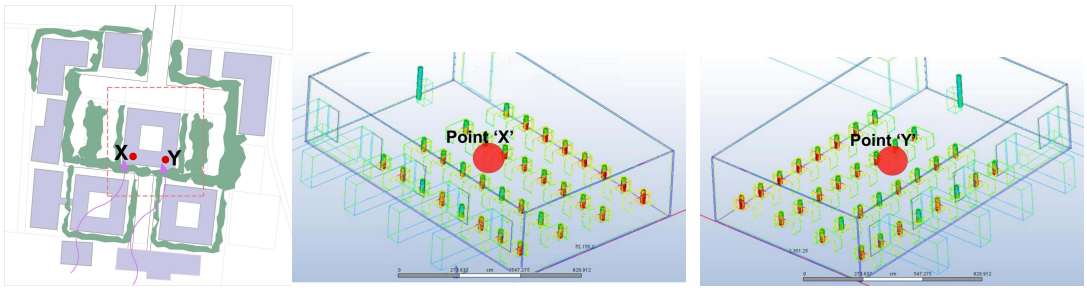
The area utilized for the study is located within the Faculty of Management Sciences building in

Baze University Abuja Campus. The major feature of this built environment which is significant in this study is the presence and proximity of shading trees. Since the closeness of the trees are considered as the major barriers against the supply of adequate wind flow for natural ventilation, air velocity measurement are used to analyze the behavior and speed of wind around this area. Figure presents the mean wind speed values obtained during the study period.



A – 6.02 m/s A – 0.9 m/s A – 0.73 m/s A – 3.4 m/s

Figure 11. Average wind speed at external measuring points A to D



X – 0.5 m/s Y – 0.6 m/s

Figure 12. Average wind speed at internal measuring points X and Y

4.1. CFD SIMULATION OF THE ENVIRONMENT

Computer fluid dynamics simulation was carried out to evaluate the wind flow patterns amidst the clusters of vegetation (tree geometry) towards naturally ventilating the buildings and classrooms. The CFD simulation is used to visualize the airflow distribution within the study area as well as the modeled classroom environment. The result of the simulation analysis is presented in Figure 13 and 14. Through the result of the CFD simulations, the behavior of airflow conditions identified in the field measurements are elucidated. Ultimately, this result emphasizes the importance of effective environmental geometry assessment, as well as highlights the critical role of appropriate layout designs for achieving effective natural ventilation in tropical urban settings

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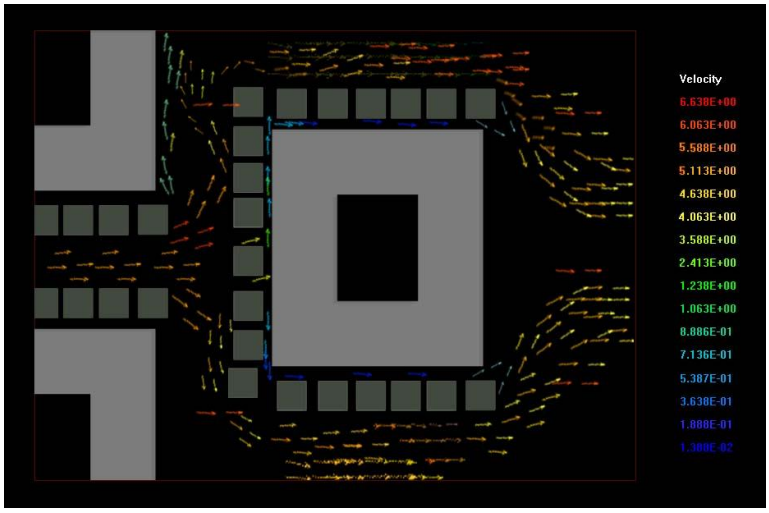

Figure 13. Simulation of airflow distribution around the study area as illustrated in Figure 10

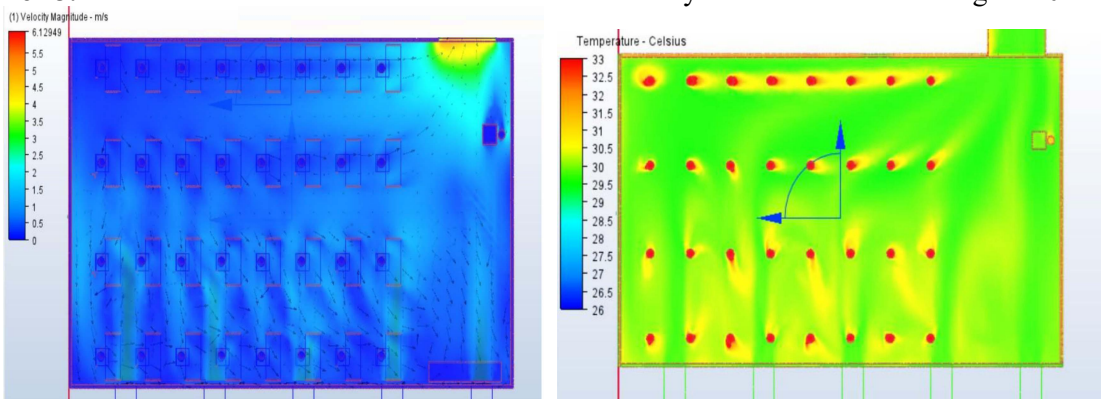

Figure 14. Simulation of airflow and temperature distribution within the classroom facing the SW end of the building

5. RESULTS AND DISCUSSION

Following the CFD simulation setup, the visualization of the airflow distribution within the study area as well as the modeled classroom environment were accomplished. The result of the simulation analysis (Figure 13) revealed the behavior of airflow conditions identified in the field measurements.

The area labeled as point “A” which is an open walkway and major wind-flow pathway to the classroom under study indicated a velocity range above 6m/s, while the immediate locations to the building walls (points “B” and “C”) showed a slowed speed of less than 1m/s. However, the wind speeds picked up at point “D” as recorded in Figure 11, where zero obstruction existed. This indicated that the non-presence of trees or other obstructive objects within the vicinity of the courtyard area aided in the improvement of the airflow. The results of the wind speeds at the 4 points (Figure 11), revealed that the wind speed at the immediate area before the windows of the building was drastically reduced from the 6m/s approach velocity to less than 1m/s at the active building fenestration/ventilation points. This indicated the extents of the obstructive effects the tree geometry has by deflecting the wind force, thereby reducing the airflow for inducing natural ventilation in the classrooms. Conversely, the internal wind speed measurement indicated the extents of the reduced ventilation value. As observed in (Figure 15), while point A recorded a higher air velocity, points B and C both recorded extremely low air velocity and internal points X and Y recorded far lesser wind velocity values.

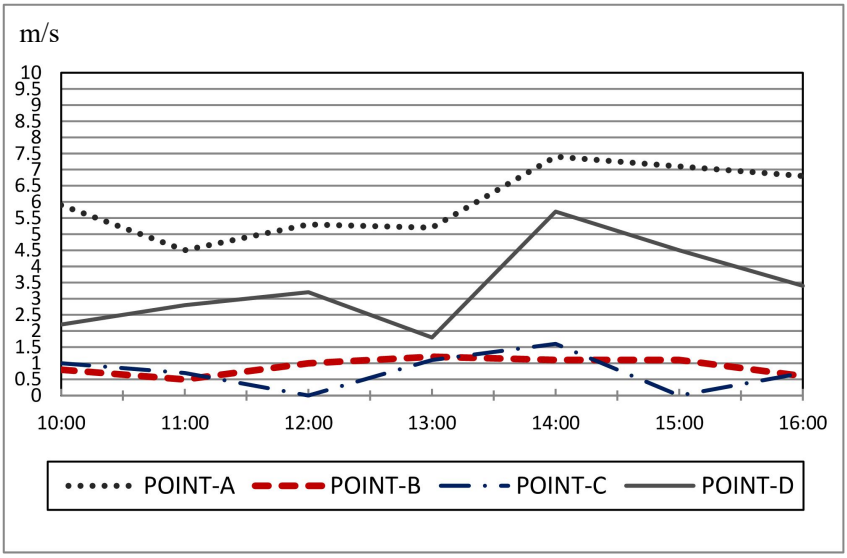

Figure 15. Comparing wind velocities at external points A,B,C & D

The impact of these reduced wind velocity is clearly demonstrated in the CFD simulation presented in Figure 14, where the interior air velocities of the classrooms indicated values lower than 1 m/s. The results as summarized in Figure 15, when compared to previous studies used as baseline case for quality of wind flow for effective wind ventilation (Aflaki et. al, 2016), reveals that the resultant conditions in the classrooms are way below sufficient for comfort level natural ventilation. The baseline levels taken from Aflaki et. al, (2016) is summarized in Table 3, suggests that wind speeds above the ranges of 2.0m/s are good for natural ventilation in hot and humid climates, while ranges above 4.5m/s are considered as gentle breeze. This indicates that the wind velocities observed in the classrooms with an average of 0.5 m/s & 0.6m/s are rarely sufficient for wind driven natural ventilation, despite the high wind velocities (above gentle breeze value) recorded all around the building.

Table 3. Description of indoor air velocity values in naturally ventilated buildings (Aflaki et. al, 2016)

S/N	Wind velocity (m/s)	Effects on Occupant comfort
1	0.05	Stagnant air, slightly uncomfortable
2	0.02	Barely noticeable but comfortable
3	0.25	Design velocity for air outlets that are near occupants
4	0.4	Noticeable and comfortable
5	0.8	Very noticeable but acceptable in certain high-activity area if air is warm
6	1.0	Upper limit for air-conditioned spaces. Good air velocity for natural ventilation in hot and dry climates
7	2.0	Good air velocity for ventilation in hot and humid climates
8	4.5	Considered a gentle breeze when felt outdoor

Ultimately, this result emphasizes the importance of effective environmental geometry assessment, as well as highlights the critical role of appropriate layout designs for achieving effective natural ventilation in tropical urban settings.

6. CONCLUSION

This study evaluated the behaviors of air flow as well as analyzed the impacts of environmental geometry on the natural ventilation potential within the Baze university campus environment. For the purpose of the study, field surveys were conducted to generate data regarding the microclimatic conditions in the study area. The data generated includes external air velocity readings at points around the selected study area, internal air velocity readings within classrooms facing the seasonal wind direction (SW) as well as proximity values of the vegetation geometry (trees) around the building under assessment. The study utilized both observatory analysis and CFD simulation to analyze and synthesize the findings within the study area. While the external wind speeds recorded higher values up to 6.02m/s around the building, the wind speeds decreased down to 0.73m/s closer to the building walls, owing to the obstruction caused by the presence of low-branching trees that are in close proximity to the building in the study area. Conversely, the internal wind speeds recorded were as low as 0.5m/s, which signified a not so good air velocity for ventilation in hot and humid climates (Aflaki et. al, 2016). The general conclusion is that the surrounding street elements like trees and landscaping structures prevail in the diversion and consequent reduction of wind speed needed for natural indoor ventilation.

Consequently, this research portrays the reality that results when building designers and landscaping engineers fail to synergize in the design of comfort-based built environments. Recommendations to be derived from this study include:

a. Passive ventilation intended landscaping: This involves the appropriate location and arrangement of landscaping and street geometric components in locations that complement natural ventilation during the design phase.
b. CFD and Simulation enabled Design: By incorporating both CFD analysis and Simulation of environmental conditions during design phases, designers and engineers can identify and predict conditions that will enable early optimization of airflow and comfort conditions under real climatic constraints.

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