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ARTICLE

The Effect of Courtyard Geometry on Airflow Regimes for Ventilation in Tropical Nigerian Environment

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ABSTRACT

Effective natural ventilation is subject to the ambient wind flow, as well as the conditions of the micro-climate and the geometry of the built structures in the environment. Architects and designers adopt the courtyard concepts for designs in hot tropical climates owing to its unique geometrical characteristics that enable the improvement of airflow required for natural ventilation. This paper presents a review of the airflow regimes within an urban settlement as well as flow regions cultivated when winds interface with courtyard buildings. The impacts of these winds are further studied against different courtyard configurations using schematic analysis based on the *H/W* ratios, to predict the natural ventilation potentials of various courtyard building types.

Keywords: Courtyards; Airflow regimes; Courtyard geometry; Natural ventilation; Courtyard ventilation

1. Introduction

Courtyards are open areas surrounded by walls of buildings. In building design, they are special voided elements typically located in a building's centre to serve different functions.

Courtyard application in buildings can be traced as far as the BC 6400 within the Jordan Valley where homes were constructed around open square spaces surrounded by small room units [1]. This practice is pronounced within the Ancient Roman and Chinese cultures where central courts and gardens were built to be surrounded by homes for luxurious living. Also, courtyard concepts became renowned in warmer climatic regions in the 20th century for the purposes of bringing sunlight into living quarters and infusing aeration within interior living spaces [2]. The advantages of courtyard buildings cut across their

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potential for introducing cross ventilation in room spaces and improvement of thermal comfort through air movement during the very hot seasons. This potential has remained the most significant value for the application of courtyards in building designs. Presently, with the advent of energy saving and sustainable building development, it is seen as the most effective passive design strategy for improving thermal comfort within tropical regions where high heat and humidity abound. Numerous studies have been conducted in the past to understand the effects and impacts that courtyard spaces pose on the building system.

This paper seeks to investigate these properties of the courtyard geometry on the natural urban airflow systems within tropical environments and how this may impact the natural driven ventilation in houses.

2. Background of study

In modern times, human settlements have evolved into complex settings accentuated by growth in development of urban environments. This evolution also resulted in transformations in the function and configuration of urban systems which impacts heavily on the universal urban climate. Research identifies the general urban climate as a critical element in the structure of the regional and global climates and thus responsible for urban liveability [3-5]. The configuration and orientation of urban buildings as well as the geometry of built-up features within the urban environment collectively influence the potential for cooling of the whole urban system through impacts on the solar access inside and outside the buildings, indoor and outdoor thermal conditions, as well as the permeability of airflow for natural ventilation [6,7]. Studies show that at any given location, the geometry of the environment is the most significant parameter that is responsible for the differences in microclimate behaviours [8]. The structure of wind field for airflow, passive ventilation and cooling in the urban environment is characterized by the formation of vertical structure that occurs in two distinct layers. On one hand, the airflow from the rural environments flows to the urban areas. This airflow system naturally adopts a new boundary condition created by the metropolitan structure of the city, hence resulting in the formation of an urban canopy sub layer characterized by the obstructed flow that extends from the ground surface to reach the building's height. On the other hand, the second layer which is the urban boundary free surface layer extends above the rooftops of buildings. It is this urban canopy sub-layer that possesses the flow properties which are influenced by the interaction between the overhead airflow at the roof tops and the geometrical features within the environment like the shape of buildings, natural topography, street patterns, urban vehicular circulation, and surrounding vegetation like trees and shrubs. Owing to the obstructive conditions, wind speeds in this urban canopy layer are largely reduced compared to the undisturbed normal wind speeds experienced in the rural settings [9]. The consequence of these reduced wind speeds is seen as a significant limitation for applying natural ventilation in dense urban environments.

In the era of sustainable building designs, natural wind driven ventilation is regarded as one of the passive cooling strategies with the most cost saving value [10,11]. Various design strategies are adopted for infusing natural ventilation in building designs, and the courtyard design system is amongst the most significant. The architectural configurations of buildings and adopted geometrical forms are considered as the main parameters that influence courtyard efficiency for wind trapping and natural ventilation. This paper thus presents some of the significant courtyard configurations for the purpose of reviewing the airflow patterns required for wind driven ventilation.

2.1 Significance of airflow for natural ventilation in the study area

This study utilized the local Nigerian environment owing to its significant tropical climate. Nigeria lies above the equator between latitudes 4° and 14°N, and longitudes 2° and 15°E making it a typical tropical location. Climatically, it falls within the area labelled as a warm humid region. Its warm and humid climate, just like those of other sub-Saharan countries within the West African region, is influenced by two major factors [12], which are:

Daily heating and cooling of the Sahara Desert land area; and Heating and cooling of the Atlantic Ocean.

These two phenomena stated above produce the distinctive dry and rainy seasons. It also generates distinctive wind patterns (**Figure 1**), ideally characterized by the North-Easterly (Harmattan) winds which are experienced from the months of April to September and the South-Westerly (Monsoon) winds also experienced between the months of November to March [12]. These wind patterns form the basis for building orientation adopted by architects in passive cooling (ventilation) designs.

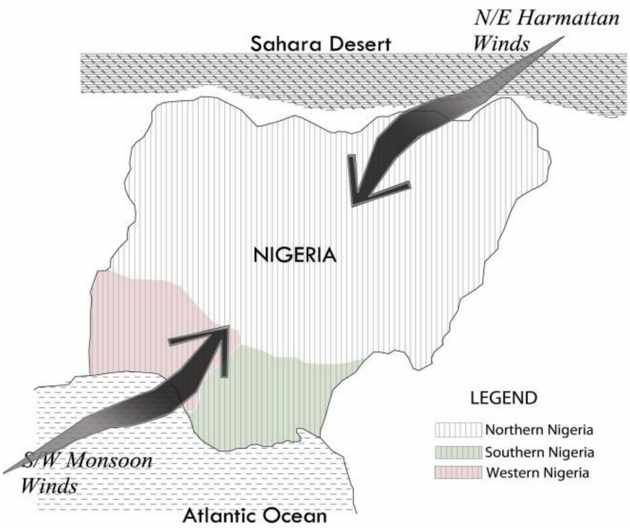


Figure 1. Map of Nigeria showing the major seasonal wind patterns.

Concepts of passive cooling in tropical climates like Nigeria often consider air movement values as significant factors in determining thermal comfort. Studies on thermal comfort suggest that the effects of air temperature, humidity and air movement in hot climates can be used to determine the human thermal responses [13]. In hot climates, the significance of air movement and relative humidity are mostly vital where the heat lost via evaporation often prevails. Research in tropical areas identifies the comfort limits for naturally ventilated spaces to range between 26 degrees to 31 degrees, with wind speeds of 1.0 m/s [14]. More so, within these hot humid (tropical) climates, high wind speeds are often required to maintain thermal comfort ranges at higher temperatures [15]. These impacts of natural ventilation mentioned above can be induced by wind pressure, temperature difference/Stack-effect or humidity difference [16]. Study shows that natural ventilation systems are dependent on the pressure differences for moving fresh air across buildings. These pressure differences that result from wind flow are generated by temperature variations [17,18]. Research on airflow regimes identifies that incident flow conditions, as well as the urban environment and building geometry can influence wind driven pressure distribution and wind direction [19]. Thus the relationship between building design and application of wind driven natural ventilation may lie in the performance of indoor air by the air pressure applied onto a building façade and the varying conditions of the outdoor air movement [20].

2.2 Courtyard configurations in the study area

Courtyards as architectural design style have been incorporated into buildings for centuries. Apart from serving the purpose of a central gathering court for family and other activities, its major function lies in its adoption as air-wells for fresh air intake as well as serving the function of light-wells for providing lighting to surrounding spaces through its open sky features [21].

Different configurations of courtyards are adopted in different locations to serve a variety of functions ranging from social gathering areas to passive lighting and ventilation purposes. In the tropical Nigerian environment, the primary function of courtyards is that of passive cooling through natural ventilation. Studies of existing courtyard configurations all across Nigeria identified a variety of compositions that could be categorized as vernacular, colonial, post-colonial and modern (**Table 1**). This concept of architecture is seen in various building types (**Table 2**), ranging from residential buildings to administrative, institutional, health, educational, and multi-functional buildings [22].

Table 1. Classification of courtyard building typology found in Nigeria.

			
Vernacular	Colonial	Post-colonial	Modern

Table 2. Various functions of courtyard buildings in Nigeria.

			
Institutional	Health	Administrative	Residential

3. Study methods

This study utilized geometrical information on courtyard building types in the study location to predict the Natural ventilation potentials. To do this, a review of the courtyard building types in selected locations in Nigeria is conducted and through this review, different courtyard configurations are identified. The mode of selection is meant to identify significant typologies and the most common courtyard configurations adopted across the country. It further utilizes a schematic analysis based on the courtyard geometry (*H/W* ratios) of each configuration to calculate the regions of airflow (recirculation region and ventilated region). A typical geometry in this case is defined by the characteristic ratio (referred to as aspect-ratio), which comprises the ratio of the building height *'H'* to that of its width *'W'*. In the case where the building presents an aspect-ratio that is approximately or equal to 1.0 it is referred to as *high*. However, when its aspect-ratio falls below 0.5, it is then referred to as *low or moderate*, whereas an aspect-ratio of above 1.5 to 2.0 signifies a *deep* courtyard. The typical length of a courtyard *'L'* expresses the distance along the building walls. The result of these calculations provides the details of the airflow regime which could be used to predict the natural ventilation potential for each courtyard building type.

4. Analysis and results

4.1 Effects of airflow systems on buildings

Studies of airflow regimes in built-up settlements regard the geometry of the elements that form the urban fabric (relative to the height-to-width ratio) of buildings and the development orientations as the most significant parameters that influence urban microclimatic changes [23]. Such parameters as urban geometry are directly responsible for the quality of airflow at street levels and solar access, which in turn affects the quality of natural ventilation [24]. Since air movement in urban settlements is dependent on the interaction between impending winds within the built environment, so also does the pattern of existing wind alter in pattern when it flows through buildings. This impending airflow over urban settlements is subdivided into two layers that occur at the urban canopy level and the urban boundary level. With the impacts of the barriers (elements of urban geometry), airflow within the canopy urban level is often obstructed more than that of urban boundary level, resulting in wind driven air circulation used for natural ventilation in buildings. This entire circulation feature as explained above is regarded as the Airflow

Regime [25]. The potentials of the wind circulation within urban developments are dependent majorly on the orientation and geometry (Height/Width and Length/Width) of built-up elements. A study on airflow regimes identified two regions that generate the wind patterns required for natural ventilation. The development of wind flows within these regions is likewise influenced by geometry, and their fluxes rate differently owing to building canopies and site conditions. According to a study of canyons by Oke (1987) and Hunter (1992), when the wind flow above the roof levels is perpendicular to the building (depending on the dimensions of the opening), the flow could be described in terms of three regimes in the urban air circulation system. In the case of wide canyons with *H/W* ratio < 0.3, the boundary building units are well spaced, hence acting as isolated roughness elements as the airflow travels down-wind before it encounters the next obstacle. However, as the building units become narrower with *H/W* ratio ≈ of 0.5, the obstructed airflow lacks sufficient travel distance to readjust, hence resulting in a wake interference flow. Consequently, in the case of regular canyons *H/W* ratio ≈ of 1, the majority of the wind flow skims over the canyon, thus generating the skimming flow characterised by the development of a single vortex inside the canyon [25,26]. These three flow regimes (**Figure 2**) that are significant in the urban air circulation system are listed as:

i. skimming flow regime
ii. wake interference flow regime and
iii. isolated roughness flow regime

4.2 Classification of courtyard configurations

Building features and geometry are among the key parameters that outline a courtyard's potential in trapping wind for purposes of natural ventilation. This paper studies the relationship between courtyard proportions and the airflow patterns that may develop within them. By understanding the behaviours and patterns of airflow, building designers will be equipped with ideas necessary for the composition of building forms that will enable the achievement of naturally ventilated buildings. For the review of airflow, different outlines of courtyards found in various typologies and courtyard configurations commonly adopted across Nigeria were collected and classified based on their geometrical characteristics. The selected courtyard buildings characterize the major features of each category picked from the three (3) main geopolitical regions in Nigeria (North, South and West) as shown in **Figure 1**. The geometrical forms of these courtyard buildings are regarded as the major containers for wind flow collections in courtyards. Classification of the identified typologies is shown in **Table 3**, indicating the ranges of the horizontal (*W*) and vertical (*H*) proportions.

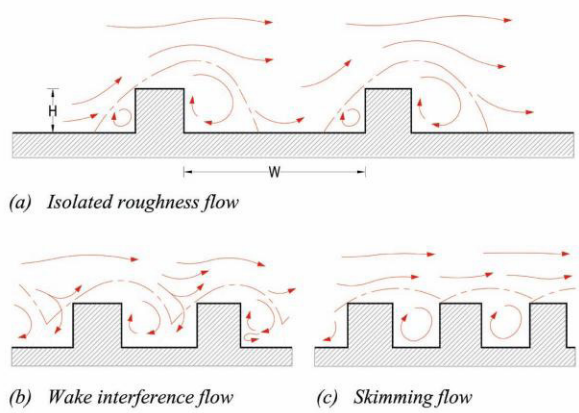
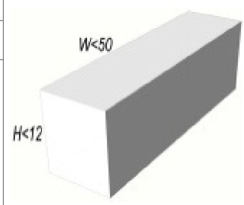
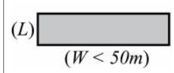
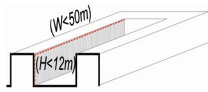
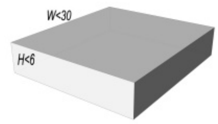
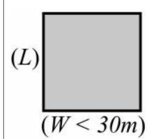
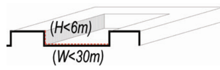
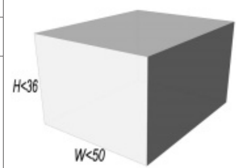
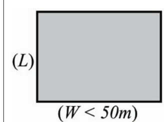
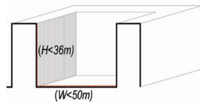
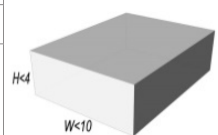
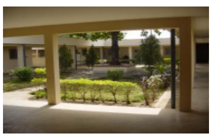
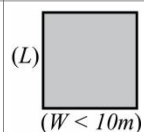
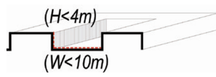
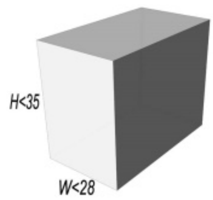
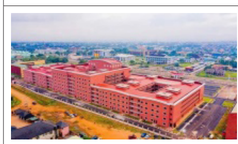
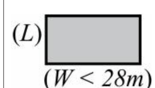
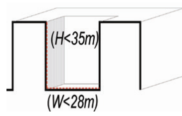
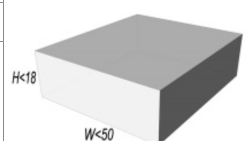
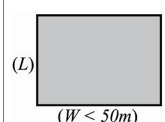
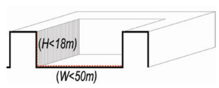
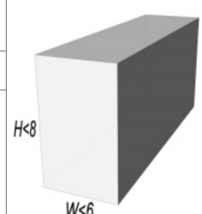
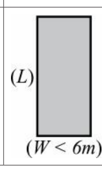
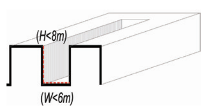


Figure 2. Representation of the three flow regimes in the urban boundary layer [25]. *(a)* is referred to as the isolated roughness flow regime, *(b)* is referred to as the wake interference flow regime, *(c)* is referred to as the skimming flow regime.

4.3 Determining the regions of airflow in courtyards

A review of the three airflow regimes responsible for the urban air circulation system identified two distinct regions of development [25] as shown in **Figure 3**. The more active system termed the Ventilated Region, forms when the space within the courtyard cavity is sufficiently wide and this region provides the unobstructed flow for natural wind-driven ventilation. Conversely, a Recirculation Region develops at the near wake of buildings and in the case of courtyard buildings (dependent on building orientation), this system provides a weaker reused airflow system.

Table 3. Various configurations of courtyards are applied in different locations in Nigeria.

Building reference	**Types**		**H/W ratio**		**Cavity geometry**
NIPSS Kuru, Jos.	NARROW		0.24		
Northern Nigeria	**H**	**W**	**Plan**	**Section**	
	< 50 m	< 12 m			
Baze University Admin Building, Abuja	WIDE		0.20		
Northern Nigeria	**H**	**W**	**Plan**	**Section**	
	< 30 m	< 6 m			
Federal Secretariat Awka, Anambra	HIGH-RISE		0.72		
Southern Nigeria	**H**	**W**	**Plan**	**Section**	
	< 50 m	< 36 m			
Edo State University PG Students' Hall	LOW-RISE		0.40		
Western Nigeria	**H**	**W**	**Plan**	**Section**	
	< 10 m	< 4 m			
Delta State Secretariat complex	DEEP		1.25		
Southern Nigeria	**H**	**W**	**Plan**	**Section**	
	< 28 m	< 35 m			
BUH Hospital, Abuja	MODERATE		0.36		
Southern Nigeria	**H**	**W**	**Plan**	**Section**	
	< 50 m	< 18 m			
Students' Hostel Choba University of PH Rivers	TIGHT		1.30		
Southern Nigeria	**H**	**W**	**Plan**	**Section**	
	< 6 m	< 8 m			

From **Figure 3**, the length of the recirculation region (*Lr*) is relative to the building height. According to studies, the value of the ratio of the length of the recirculation region and building height (*Lr*/*H*) depends on the turbulence levels in the urban boundary layer and the building geometry. Wind driven ventilation is achieved when the high speed flow from above the building roof level in the ventilated region is conveyed to ground level, thereby resulting in the development of internal bound flow layers along the surfaces. Equally, the continuous flow of wind slows within the recirculation region mostly due to the presence of milder moving air induced by the obstructive sides of the building [27]. With the distinctive climate of Nigeria which runs a characteristic NE flow (between the months of November to March) and a SW flow (between April to September), the direction of wind flow for natural ventilation is often generated from these (North-easterly and South-westerly) directions annually. This condition usually prompts the orientation of buildings by designers along these distinctive seasonal wind paths, ensuring that each side of the building is exposed to the wind paths at different seasons.

Through this study, the likely performance of each courtyard configuration for effective natural ventilation can be predicted. **Table 4** shows the predicted performance of each configuration following the ratios of recirculation and ventilated regions formed in each courtyard cavity configuration.

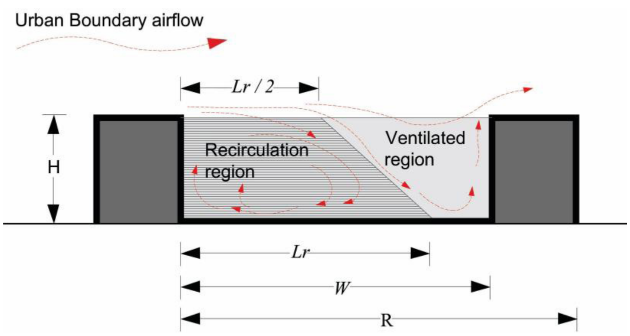


Figure 3. Typical courtyard cross-section showing the Ventilated and Recirculation regions.

As observed in **Figure 3** above *Lr* indicates the length of the recirculation region. *Lr*/*H* calculates the ratio of the length of the recirculation region and building height.

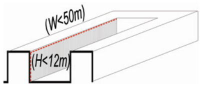
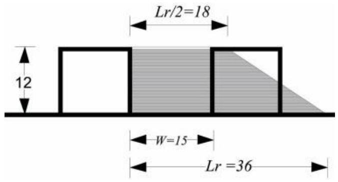
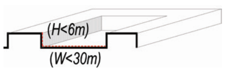
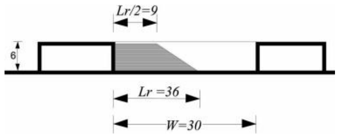
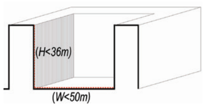
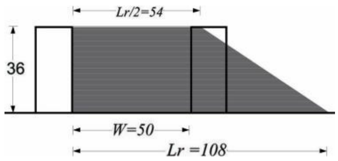
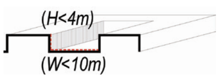
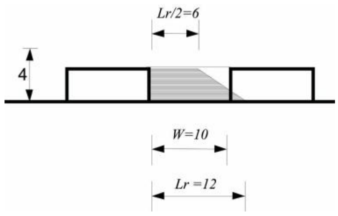
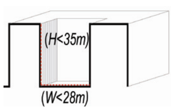
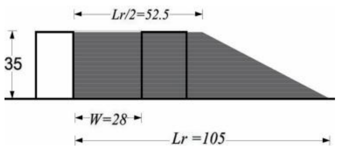
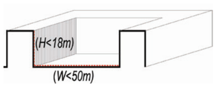
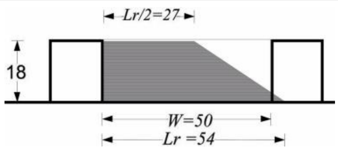
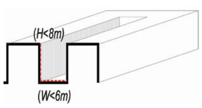
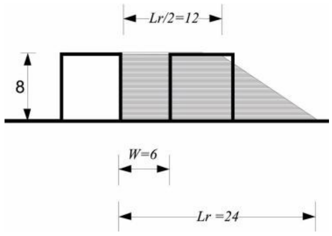
Following the study by Oke (1987), $Lr < W$ refers to the isolated roughness flow regime, whereas $Lr/2 < W < Lr$ refers to the wake interference flow regime and $W < Lr/2$ refers to the skimming flow regime. Following the study, the value of *Lr*/*H* falls between 2 and 3. This is set according to the value of $Lr < W$, so that $H/W < 1/3$ in the case of wide canyons, ensuring that the recirculation region does not encroach onto the downstream facade (hence realizing isolated flow regime). For moderately wide canyons, it suggests that $Lr/2 < W < Lr$, so that $1/3 < H/W < 2/3$, following this, the recirculation region then rises to encroach on the downstream façade (achieving the wake interference flow regime). In the case of the Skimming flow regime which occurs in narrow street canyons, it suggests that $W < Lr/2$, so that $H/W > 2/3$, in this case, the entire canyon volume is occupied by the recirculation regime [25].

5. Discussion

Following the analysis of the airflow systems in the different courtyard configurations, this study identified the potential scenarios that may ensue relative to the geometry of the courtyard building types examined. **Table 4** presents the flow regime schematics for the dissimilar *H/W* configurations while assuming the value of $Lr/H = 3$. The objective of this is to graphically identify the extent of ventilated and recirculation areas accessible for natural ventilation as well as to ascertain the extent of obstruction produced by the building geometry itself on the airflow in this region.

From the analysis as shown in **Table 4**, it is evident that the Wide Courtyard typology with a courtyard (*H/W*) ratio of 0.2 is the only configuration that results in an ***isolated roughness flow***. An isolated roughness regime occurs between well-spaced building units with reduced obstruction for urban boundary airflow that drives ventilation in buildings. On the other hand, the Low-rise and Moderate typologies with courtyard (*H/W*) ratios of 0.4 and 0.36 respectively present the ***wake interference flow*** with limited ventilated airflow regions to the windward face of

Table 4. Predicted airflow routine of the different courtyard configurations.

Courtyard type	Courtyard configuration	Courtyard ratio	Projected airflow systems	Resultant airflow regime
NARROW		0.80		Skimming regime
WIDE		0.20		Isolated roughness regime
HIGHRISE		0.72		Skimming regime
LOW RISE		0.40		Wake interference regime
DEEP		1.25		Skimming regime
MODERATE		0.36		Wake interference regime
TIGHT (Width)		1.30		Skimming regime

the courtyards. This limited airflow from the urban boundary layer occurs due to obstruction caused by the higher building geometry, hence permitting ventilated airflow on partial areas of the internal courtyard façade. The other four types which include the Narrow, High-rise, Deep and Tight configurations with courtyard (*H/W*) ratios of 0.8, 0.72, 1.25 and 1.3, all result in ***skimming flow***. The skimming flow regime as discussed earlier is totally dependent on airflow within the urban canopy layer owing to obtrusiveness from the geometry of the narrower courtyard widths relative to the building heights. The main feature of skimming airflow is the slow wind speeds from the recirculation regions resulting in weaker velocity for driving natural ventilation in the buildings.

These three scenarios are summarized in **Table 5**, showing the courtyard (*H/W*) ratio with the best potential for natural ventilation.

Table 5. Comparison of courtyard geometry (*H/W* ratio) and natural ventilation potentials.

	Courtyard (*H/W*) ratio	**Extant airflow regime**	**Natural ventilation potential**
1.	0.1-0.2	Isolated roughness airflow regime	Good
2.	0.3-0.5	Wake interference airflow regime	Fair
3.	0.6-1.0 and above	Skimming airflow regime	Poor

6. Conclusions

In conclusion, the benefits of courtyard buildings cut across introducing cross ventilation in room spaces and improving of thermal comfort through air movement in hot tropical environments. Through this study, the natural wind-driven ventilation prospects in each of the courtyard configurations studied admit that the wider-spaced design type is most suitable. This also signifies that the *H/W* ratio that falls between the ranges of 0.1 and 0.2 is most effective for introducing airflow with significant wind speeds for effective cross ventilation. Nevertheless, the effectiveness of employing natural ventilation in various locations against different courtyard configurations is also hugely dependent on the building's orientation and planning. With the presence of complex wind paths caused by the urban airflow structure and the boundary conditions created by the metropolitan structure of the city, which results in the formation of obstructed wind flow along the urban canopy sub-layer, planners and passive building designers are often challenged with attaining quality airflow access into buildings. Equipped with the knowledge of the behaviour of airflow regimes and understanding the seasonal wind flow systems, designers of courtyard buildings may apply orientation coupled with the most appropriate courtyard configuration in order to maximize wind trapping for natural ventilation.

Author Contributions

In this study, the main author Akubue Jideofor Anselm, composed the structure of the work as well as formulated the research methods and analysis. This was driven by the need to develop a schematic/graphical mode for visualizing the airflow regions via geometrical calculations. The main author likewise carried out the calculations of the airflow regions using the identified courtyard geometrical configurations for the prediction of ventilation potentials.

The secondary author, Adesina Damilola Omusi carried out the surveys of the courtyard typologies and generated the configurations utilized for the calculations of the airflow regions.

Conflicts of Interest

There are no conflicts of interest.

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References

[1] Bar, S., Cohen-Klonymus, H., Pinsky, S., et al., 2017. Fazael 7: A large Chalcolithic architectural complex in the Jordan Valley, the 2009-2016 excavations. Journal of the Israel Prehistoric Society. 47, 208-247.

[2] Yakubu, P.W., Alibaba, H.Z., 2018. Performance of courtyard systems of housing in hot and humid climate (Bauchi, Nigeria). International Journal of Civil and Structural Engineering Research. 6(2), 128-139.

[3] Srivanit, M., Kazunori, H., 2011. The influence of urban morphology indicators on summer diurnal range of urban climate in Bangkok metropolitan area, Thailand. International Journal of Civil & Environmental Engineering. 11(5), 34-46.

[4] Grimmond, C.S.B., Roth, M., Oke, T.R., et al., 2010. Climate and more sustainable cities: Climate information for improved planning and

management of cities (producers/capabilities perspective). Procedia Environmental Sciences. 1, 247-274.

[5] Huang, L., Li, J., Zhao, D., et al., 2008. A fieldwork study on the diurnal changes of urban microclimate in four types of ground cover and urban heat island of Nanjing, China. Building and Environment. 43(1), 7-17.

[6] Ali-Toudert, F., Mayer, H., 2006. Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. Building and Environment. 41(2), 94-108.

[7] Akubue, J.A., 2019. Effects of street geometry on airflow regimes for natural ventilation in three different street configurations in Enugu City. Different Strategies of Housing Design. IntechOpen: London.

[8] Oke, T.R., 1988. Street design and urban canopy layer climate. Energy and Buildings. 11(1-3), 103-113.

[9] Santamouris, M., 2001. Energy and climate in the urban environment. James and James Science Publishers: London.

[10] Zhai, Z., 2006. Application of computational fluid dynamics in building design: Aspects and trends. Indoor and Built Environment. 15(4), 305-313.

[11] Su, Y., Riffat, S.B., Lin, Y.L., et al., 2008. Experimental and CFD study of ventilation flow rate of a Monodraught™ windcatcher. Energy and Buildings. 40(6), 1110-1116.

[12] Ojo, O., 1967. The climates of West Africa. Heinemann: London.

[13] IHVE Guide Book C, 1970. Institution of Heating and Ventilation Engineers: London.

[14] Boutet, T.S., 1987. Air movement. A manual for architects controlling and builders. Mc-Graw Hill: New York.

[15] Mallick, F.H., 1996. Thermal comfort and building design in the tropical climates. Energy and Buildings. 23(3), 161-167.

[16] Oyem, A.A., Igbafe, A.I., 2010. Analysis of the atmospheric aerosol loading over Nigeria. Environmental Research Journal. 4(1), 145-156.

[17] Feustel, H.E., 1999. COMIS—an international multizone air-flow and contaminant transport model. Energy and Buildings. 30(1), 3-18.

[18] Mistriotis, A., Arcidiacono, C., Picuno, P., et al., 1997. Computational analysis of ventilation in greenhouses at zero-and low-wind-speeds. Agricultural and Forest Meteorology. 88(1-4), 121-135.

[19] Kim, Y.C., Yoshida, A., Tamura, Y., 2012. Characteristics of surface wind pressures on low-rise building located among large group of surrounding buildings. Engineering Structures. 35, 18-28.

[20] Ghiaus, C., Allard, F., 2005. Natural ventilation in the urban environment: Assessment and design. Buildings energy and solar technology. Earthscan: London.

[21] Saxon, R., 1994. The atrium comes of age. Longman: London.

[22] Markus, B., 2016. Review of courtyard house in Nigeria: Definitions, history, evolution, typology, and functions. AFRREV STECH: An International Journal of Science and Technology. 5(2), 103-117.

[23] Todhunter, P.E., 1990. Microclimatic variations attributable to urban-canyon asymmetry and orientation. Physical Geography. 11(2), 131-141.

[24] Nakamura, Y., Oke, T.R., 1988. Wind, temperature and stability conditions in an east-west oriented urban canyon. Atmospheric Environment. 22(12), 2691-2700.

[25] Oke, T.R., 1987. Boundary layer climates. Routledge: London.

[26] Hunter, L.J., Johnson, G.T., Watson, I.D., 1992. An investigation of three-dimensional characteristics of flow regimes within the urban canyon. Atmospheric Environment. Part B. Urban Atmosphere. 26(4), 425-432.

[27] Townsend, A.A., 1976. The structure of turbulent shear flow: Boundary layers and wall jets, 2nd edition. Cambridge University Press: Cambridge.