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Chapter

Effects of Street Geometry on Airflow Regimes for Natural Ventilation in Three Different Street Configurations in Enugu City

Jideofor Anselm Akubue

Abstract

Efficient natural ventilation is dependent on the micro climate conditions of an urban environment. This is affected by ambient wind flow, radiation and air temperatures. The airflow within the urban street can be cultivated into two regions. The first is a recirculation region, which forms in the near wake of each building. The Second is a ventilated region downstream of the recirculation region, formed when the street is sufficiently wide. The development of the flow into these two regions depends on geometry. This chapter looks at the impacts of street geometry on these regions of airflow cultivation in three different street configurations in high density residential settlements in Enugu city. It utilized schematic analysis of airflow regimes to identify the behaviors of flow in these street configurations relative to the height and width ratios of the street canyon. This schematic analysis can be utilized in preliminary design studies by city and building designers for justifying street dimensions and configurations in tropical regions where natural ventilation is paramount.

Keywords: urban street canyon, street geometry, street ventilation, natural ventilation, canyon effect

1. Introduction

Achieving natural ventilation is subject to the micro climate conditions of an urban environment. This is dependent on the ambient wind flow, radiation and air temperatures of the location. At the micro level, the urban space geometry is the most relevant parameter responsible for the microclimate variation [1]. Recent studies on urban air flow conditions identified the structure of wind field as characterized through the creation of vertical structure which occurs in two layers. When the air coming from the rural environments flows to the urban areas, it naturally adopts the new boundary conditions created by the city structure, thus resulting in the formation of the obstructed urban canopy sub layer, which is extended from the ground surface up to the buildings height, while the urban boundary free surface layer extends over the roof-tops. This urban canopy sub layer possesses specific

flow properties which are defined by the interface between the air flow above the roof tops and the prevailing local conditions within the environment like the shape of buildings, street patterns, urban vehicular circulation, natural topography and the surrounding local landscaping structures like trees and shrubs. Wind speed in this canopy layer of the urban structure is generally decreased compared to the undisturbed normal wind speeds. Because of the reduction of the wind speed in urban street canyons, there is significant limitation to the extent natural ventilation can be applied in dense urban environments [2]. Designers of urban spaces are mostly unfamiliar with the thermal comfort problems arising from the relationship between urban forms and local climatological conditions [3]. Due to this, many urban settlements do not respond to contextual climatic conditions. The common practice of using universal meteorological data gotten from stations that are located in unobstructed areas of the city like the airports or isolated fields may result in inaccuracies regarding the air flow in typical urban buildings [4].

Recent trends in urbanization calls for sustainable ideas tailored towards improving thermal comfort. Understanding the flow pattern and wind speed in urban street canyons is therefore necessary for analyzing the natural ventilation potential of urban buildings, especially in the tropics which is characterized by high temperatures and humidity. The impacts of urbanization, the city heat island effects coupled with global warming contribute to the increase of the peak cooling loads and electricity consumption for space cooling purposes, owing to this and more, it is vital to optimize building and city designs in terms of energy demands that considers local urban microclimates.

2. Description of study

The potential for airflow for natural ventilation in urban streets is dependent on its configuration matrix. This study aims to examine the elements of street geometry that affect the flow system within the urban street. Firstly, it highlights the theoretical basis for the airflow studies in urban streets, it then identifies the primary influences, behaviors and parameters of flow within street canyons relative to natural ventilation. These parameters, which include the measurements of airflow recirculation and ventilation regions affected by height and width ratios, are believed to have major effects on the airflow regimes experienced in urban streets.

Using Enugu metropolitan area as a case, the study utilized schematic analysis process to examine three major street configurations that stand out in the residential districts. This process forms a basis for the analysis of airflow regimes and its effects on natural ventilation. Using the parameters mentioned above, each of these street configurations in the Enugu residential district is analyzed in order to justify the effective street size for natural ventilation in this region. The study identified the possibility of wind flow reduction in urban street canyons, because of this reduction, there exists a significant limitation in the extents natural ventilation may be utilized in dense urban settings like the tropical settlements in Enugu city.

Enugu city (6.26° North and 7.29° East) is located in the Southeastern part of Nigeria. **Figure 1** shows the climatic data of Enugu. Its climate is classified as a tropical rain forest with a derived savannah. The city is set on an altitude of 304.7 m above sea level, its climate is naturally humid and this humidity is regarded as oppressive between March and November. Its average maximum temperature stands at 34.9°C, with average lows of about 22.3°C and its annual mean temperature is about 26.7°C. Typical with the rest of West Africa, the rainy and dry seasons are the only weather periods in Enugu. The average hourly wind-speed in Enugu area experiences significant seasonal variations over the course of a year. For instance, the windier part

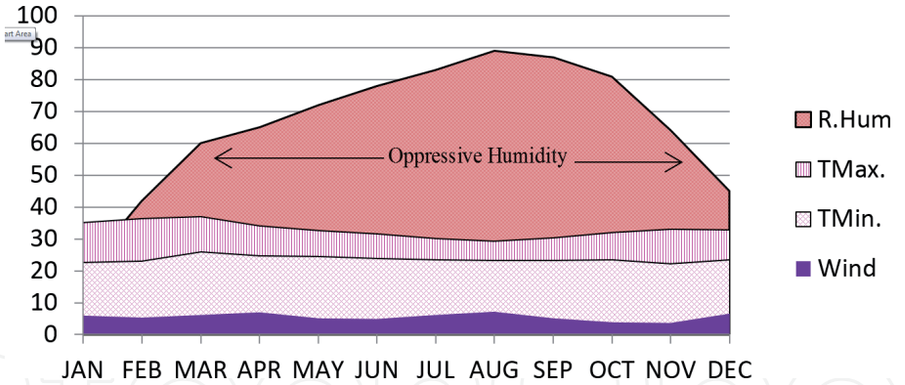


Figure 1.
Climatic data of Enugu City (source: NIMET year ended 2017).

of the year lasts for 7 months (between March and September), with average wind speed of 5.5 m/s. The windiest month of the year is usually August, with an average wind speed of 7.1 m/s. Typical wind path comes relatively from the west for an average of 10 months (termed the monsoon season), ranging from January to November, with peak percentage of about 75% occurring in July. Also, the wind direction changes to northerly for 2 months (termed the Harmattan season) from the months of November to January, with 41% occurring in the peak month of January. The wind data used in this study were obtained from the Nigerian Meteorological Agency (NIMET).

3. Elements of street geometry in urban settlements

The urban street has evolved from the original context as defined by the Latin word strata (meaning *"a paved road"*). In modern times, the function of the street in a built environment consists of more than the conventional roadway. Streets provide accessibility, connectivity, circulation, as well as infrastructural network for human settlements. As human activities grow, the function and configuration of a street system transforms especially in urban settlements. These transformations affect the micro climate environment within the street level as well as the universal urban environment. Urban climate is a critical factor which affects regional and global climates and consequently urban livability [5–7]. Geometry and orientation of an urban street affect outdoor and indoor environments, solar access inside and outside the buildings, the permeability to airflow for urban ventilation, as well as the potential for cooling of the whole urban system [8]. A typical urban street is comprised of stationary and mobile elements which form barriers that collectively affect the flow of wind within the streets. Owing to the presence of these obstacles like buildings, trees and street furniture, the air flow through the canopy layer is frequently obstructed compared to the air flow within the boundary layers. These results in the gentler airflow observed within an urban canopy layer compared to the airflow within adjoining rural settings [9]. **Figure 2** shows a typical urban street system and the barrier elements that affect airflow within the urban canopy layer.

3.1 Configurations of urban streets in Enugu city

Urban streets in tropical cities like the city of Enugu are structured to serve the basic conventional functions of accessibility and circulation. The configuration of Enugu streets is defined by urban planning classifications. The major classifications are the high density, medium density and low density. The low and medium density areas consist mainly of single villa residential housing units, while the high density

areas consist of residential apartments. Three major residential districts stand out in these configurations (shown in **Figure 3**), these districts include:

i. Achara layout

ii. Independence layout

iii. GRA district

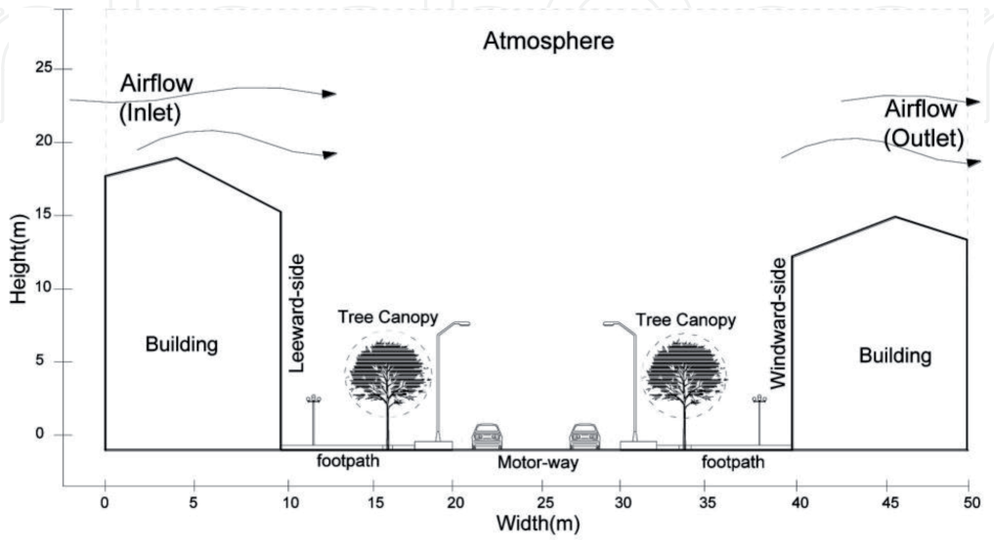


Figure 2.
Typical urban street showing the barrier elements that affect airflow within the urban canopy layer.



Figure 3.
Three major residential districts in Enugu city, representing the high, medium and low density districts.

Table 1 shows the configurations of the streets in Enugu relative to Height and Width ratios. Unlike the typical European streets characterized by activities like walkways, plazas, pavement cafes and other lifestyle facilities which define the size of the street outline (urban canyons), the sizes of the typical street canyon in Enugu city is more compact. This is condensed further by the presence of property boundary walls which is used mainly as solutions to the poor urban security.

3.2 Street canyon geometry

Street canyons are referred to as the space that is created within two similar rows of houses divided with a street way [10]. This configuration forms the major structure of modern city unit. Typical geometry of urban street canyons is defined by the characteristic ratio (aspect-ratio), which includes the ratio of the building heights *'H'* to that of the street width *'W'*. When a street canyon presents a common aspect-ratio that is approximately or equal to 1.0 without significant wall openings it is referred to as identical street canyon. When its aspect-ratio falls below 0.5, it is referred to as a shallow, while that with an aspect-ratio of 2.0 signifies a deep street canyon. The typical length of a street canyon *'L'* expresses the distance between two road intersections dividing the street into a short street canyon *'L/H = 3'*, medium street canyon *'L/H = 5'* and the elongated canyon *(L/H = 7)* [11].

Recent studies identified street geometry elements (height-to-width ratio *(H/W)*) and the street orientation as the most relevant urban parameters responsible for the microclimatic changes in a street canyon [12]. **Figure 4** illustrates the outline of a typical street canyon as parameters significant for major urban microclimate variations. These parameters directly affect the potential of airflow at street levels, solar access and its permeability and the overall urban microclimate [13, 14]. Consequently, designers and planners of urban streets are faced with the complexity of integrating seasonal climatic factors in the configuration and orientation of streets and buildings.

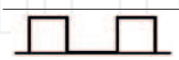
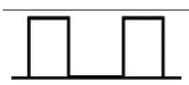
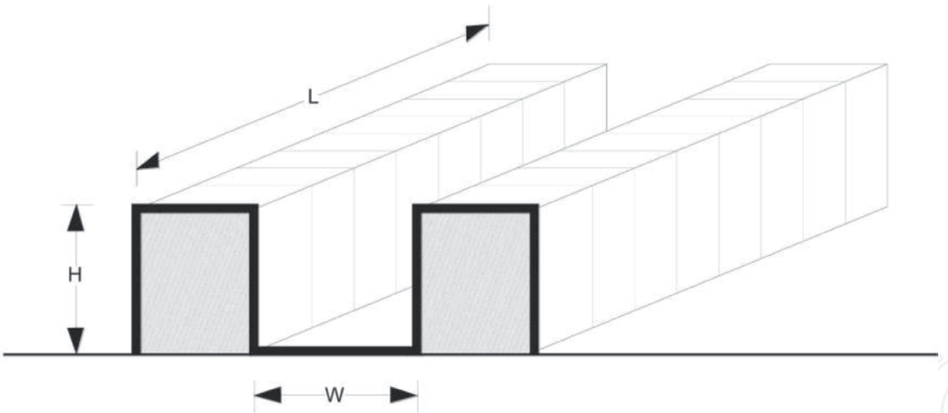
Configuration	Ratio	Planning classification	Street image	Aerial image
	0.44	*GRA district* High rent residential district (bungalows and single home units)		
	0.68	*Independence layout* High rent residential district (two floor homes made up of duplex and town houses)		
	0.94	*Achara layout* Medium rent residential district (apartments and blocks of flats)		

Table 1.
Configuration of urban streets in Enugu city.



Where:
L = road distance between two main intersections subdividing the street canyon
H = height of the buildings
W = width of the street

Figure 4.
Outline of a typical street canyon.

For instance, in the tropical hot and humid regions, the major challenges are protection from the sun and permeability of natural ventilation, which naturally influence local designers' use of shallower and compact street canyons. However, the opposite is virtually the case in colder regions where solar access is required for winter seasons, hence necessitating more openness to the sky for buildings in that region.

4. Impacts of street configuration on airflow for natural ventilation

Due to the direct impacts of urban climate and built structures on the human thermal conditions, the control of outdoors microclimate is an important issue in urban designs. The integration of adequate, well-designed planning that places urban morphology in the climatic context of its environment, contributes to sustainable development of cities [3, 15–17].

Designers of such spaces like the architects, urban planners and engineers are often unfamiliar with the thermal comfort problems arising from the relationship between urban forms and local climatological conditions. According to reference [18], it is important to forecast the thermal consequences at the early stages of the design process of urban development areas prior to construction. In the case of humid tropical climates, the cooling effect of airflow particularly at nights could mitigate effects of urban heat island phenomenon. The significance of the formation of airflow within a street canyon is essential for human health and the energy efficiency of buildings and consequently, a pleasant urban microclimate [19]. These Urban airflow patterns are determined by the interaction between approaching wind within the built environment. Conversely, the pattern of an existing regional wind is changed when it flows through a built environment [20]. The air flowing over urban areas is sub-divided into two main layers.

i. The urban canopy layer

ii. The urban boundary layer.

The urban canopy layer is the layer flowing below the level of roof tops and within the spaces between buildings. This layer is usually influenced by solar energy falling on

building facades and the ground. On the other hand, the urban boundary layer is the flow that is present above the average height of buildings. Within the urban boundary layer, heat transfer, pollutant emission, evaporation and transpiration and general contemporary urban development are the main factors that affect air conditions at this level [21]. Also, owing to the elements of street geometry (barriers as discussed above) airflow in the urban canopy layer is obstructed more than the airflow in the urban boundary layer. A secondary circulation feature driven by urban boundary layer provides airflow in an urban canyon which is strongly affected by the street orientation and geometry *(H/W and L/W)*. This circulation feature is referred to as Airflow Regimes.

4.1 Study of airflow in street canyons

The airflow within the urban street canyon can develop into two regions.

i. Recirculation region, which forms in the near wake of each building.

ii. Ventilated region (downstream of the recirculation region), formed when the street is sufficiently wide.

The development of the airflow into these regions depends on geometry, the different flow characteristics in these regions mean that the fluxes from these two regions scale differently. However, due to the complexity of building canopies, the flows through them are highly complex and site dependent [22]. **Figure 5** shows the scheme of airflow regimes.

From **Figure 6**, the recirculation region assumes a trapezoidal cross section [23]. Measurements show that the length of the recirculation region, *Lr*, is relative to the

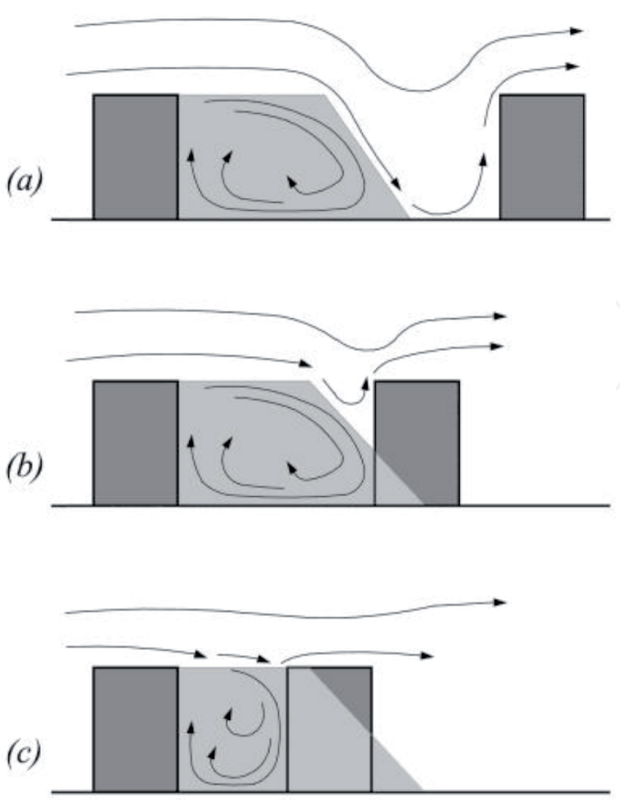


Figure 5.
Scheme of the three flow regimes in the urban boundary layer. (a) Lr < W (referred to as the isolated roughness flow regime); (b) Lr/2 < W < Lr (referred to as the wake interference flow regime); (c) W < Lr/2 (referred to as the skimming flow regime) [22].

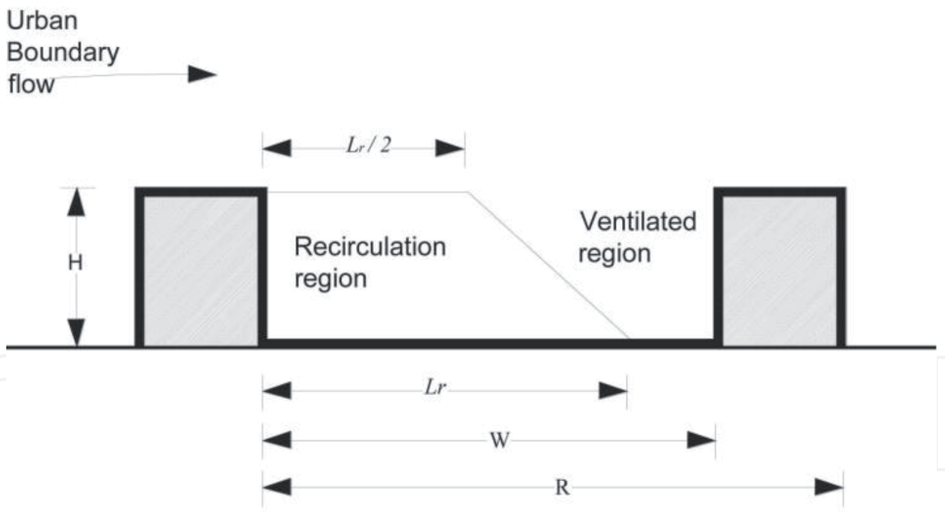


Figure 6.
Cross section of a street canyon showing the dimensions of the regions.

height of the building and so should be a scale relative to the height of the building. The value of the ratio *Lr/H* depends on the turbulence levels in the urban boundary layer and the shape of the buildings and roof.

Following the equations above, [22] suggests that *Lr/H* should be between 2 and 3. In the case of wide street canyons, it suggests that $Lr < W$, so that $H/W < 1/3$, in which case, the recirculation region does not impinge on the downstream building as can be identifies in **Figure 5a**. This it termed the "Isolated flow regime". In the case of intermediate (not so wide) street canyons, it suggests that $Lr/2 < W < Lr$, so that $1/3 < H/W < 2/3$, in which case, the recirculation region begins to impinge on the downstream building as observed in **Figure 5b**. This it termed the "Wake interference flow regime". Finally, in the case of narrow street canyons, it suggests that $W < Lr/2$, so that $H/W > 2/3$, in which case, the entire canyon volume is occupied by the recirculation regime as observed in **Figure 5c**. This it termed the "Skimming flow regime".

Inside the ventilated region, high-speed air flowing from above the roof top level is conveyed to street ground level. This causes the development of internal boundary flow layers along the surface of the street level. As this occurs, the vertical field of the wind regulates to a layer of even equilibrium with the normal surface of the street. However, the airflow in the recirculation region is dragged by recurrent high momentum injections of wind burst consistently drawn off the upstream roof. The steady burst of airflow slows as it advances around the recirculation region owing to the occurrence of gentler moving air induced by the associated street barriers [24].

4.2 Configuration of flow patterns in street canyons

As noted earlier, the conversion from one flow regime to another happens at critical combinations of *H/W* and *L/W* ratios. Understanding the configuration of patterns of airflow at different ratios is significant in determining the behaviors of flow regimes [25, 26]. **Figure 7** illustrates the characteristic interaction between the different flow regimes in urban canyons over building arrays of increasing *H/W* ratios. In the first instance, the isolated roughness flow regime occurs between buildings that are well spaced, in the event of zero interaction between the windward and leeward currents and similar to that of wind flow around isolated barriers. However, when the *H/W* ratio increases, the wakes are subjected to a disturbance, resulting to the formation of the wake interference flow. With additional increases of the *H/W* ratio the street canyon becomes isolated from the

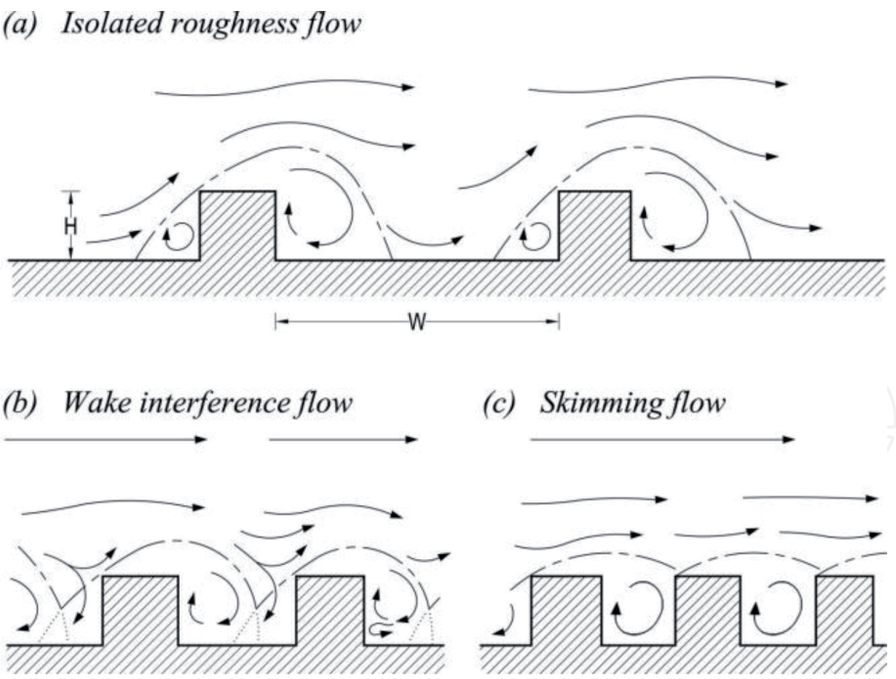


Figure 7.
The different flow regimes in urban canyons over building arrays of increasing H/W ratios [1].

flow of circulated air in the urban boundary layer, resulting in the creation of stable circulatory vortex within the canyon. This constant circulatory vortex produces the skimming flow regime that occurs mostly in the urban areas according to [27]. It could then be concluded that there is slower airflow in deep street canyons in comparison with intermediate or shallow ones.

4.3 Effects of street geometry on air temperature for natural ventilation

Studies by [28–31] show that when the wind speeds are small in urban streets, thermal effects come into play. Buildings tend to be warmer than the surrounding air and depending on the intensity of heating either the approach wind or the thermal convection dominate. The magnitude of the thermal change is dependent on many factors; including the anthropogenic heat flux in the canyon, sky view factor, and the albedo of the building facade.

Assessment of air temperature of street canyons in a hot climate in [32], show that the distribution of the air temperature recorded at the top and at the different floors of a building inside the canyon indicated that temperature above the canyon was higher during the day time than the associated temperature within the canyon. It was likewise observed that air temperatures were lower within the street canyon as the canyon is deep with limited permeation of solar radiation. This consequently results to lower surface temperatures especially towards the lower levels of the street which eventually brings about lower air temperatures. This lower temperature can be attributed to the mixing and the adjective phenomena inside the canyon that tend to regulate the air temperature.

From the study of solar access and dispersion in [1], a lower-limit of about 0.4 is assumed for ratio of *H/W* owing to the need to improve the degree of shelter for warmness and maintain a significant proportion of the temperature that is essential for the heat island warmth in colder climates. The upper limits of 0.60–0.65 ensure the maintaining of both atmospheric dispersion and solar access within the streets. Considering all factors to least a minimal extent, the most effective range of *H/W* ratio should then be between 0.4 and 0.6.

The ambient air temperature in street canyons influences the energy load of the building environment and determines the cooling potential of natural and hybrid ventilation techniques. Thermal phenomena as well as recurrent vortices which develop at the canyon corners usually dominate the air flow patterns inside the canyon. Since solar heating of the exterior facades system may create surface temperature differences that impacts on the air temperature conditions within the street canyon, such air temperature system may create local upwind along the warmer side of the facade and create a downward flow on the opposite side. In [33], clockwise vortices and counter-clockwise vortices were observed within the street canyon as the wind flow became almost perpendicular to the canyon axis, indicating that either the uninterrupted wind speed was high or that the thermal phenomena observed in the canyon corners contributed to the formation of the flow. This goes to show that the air temperature of the streets is mostly governed by more complex and regional factors than their ambient surface temperature despite the impacts of the local canyon geometry.

5. Analysis of airflow in the Enugu city street configurations

The analysis of the airflow patterns in the case of the residential streets in the tropical hot and humid Enugu city is presented using the flow regime analysis schematics for the different *H/W* configurations and assuming *Lr/H* = 3. The objective is to identify the extent of obstruction caused by existing street geometry on the airflow for Natural Ventilation in this region using schematic diagrams.

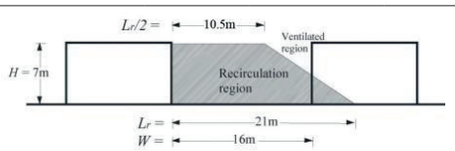
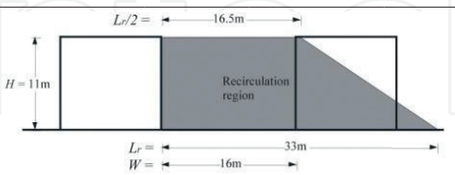
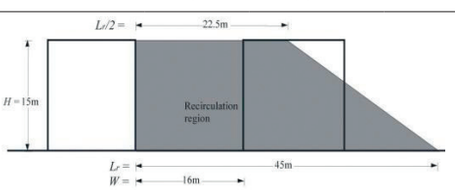
Scheme				**Result**	**Effective street width**	**Resultant airflow regime**
				*Lr/2 < W < Lr* & *1/3 < H/W < 2/3*	Intermediate-wide	Wake interference flow
H/W	*Lr/H*	*Lr*	*Lr/2*			
0.44	3	21 m	10.5 m			
				*W < Lr/2* & *H/W > 2/3*	Narrow	Skimming flow
H/W	*Lr/H*	*Lr*	*Lr/2*			
0.68	3	33 m	16.5 m			
				*W < Lr/2* & *H/W > 2/3*	Narrow	Skimming flow
H/W	*Lr/H*	*Lr*	*Lr/2*			
0.94	3	45 m	22.5 m			

Table 2.
Schematic analysis of the airflow regime for the three main street configurations in Enugu city.



Figure 8.
Varieties of concrete walls used as boundary and party fence in Enugu city.

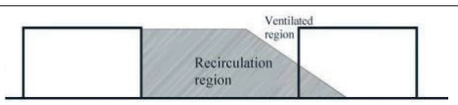
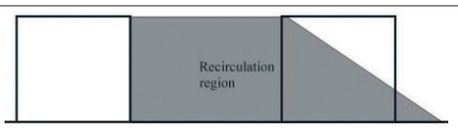
Configuration schematic	Natural ventilation prospects
Configuration 1 (0.44): GRA district 	*Intermediate-wide street* • Allows for continuous airflow from the urban boundary layer to the buildings (ventilated region), due to the lower heights of the buildings. • Unobstructed wind flow from urban boundary layer at the windward face of the buildings • Tendency of faster airflow for Natural ventilation
Configuration 2 (0.68): Independence layout 	*Fine-narrow street* • Allows airflow mostly at the urban canopy layer • Wind flow is skimming type as it is mostly re-circulated airflow. • Slower winds lack the speed for adequate permeability of Natural ventilation • Natural ventilation in buildings can be improved by applying openings on the un-shaded faces in the schematic (ventilated region)
Configuration 3 (0.94): Achara layout 	*Narrow street* • Allows airflow mostly at the urban canopy layer • Wind flow is skimming type as it is mostly re-circulated airflow. • Slower winds lack the speed for adequate permeability of Natural ventilation • Natural ventilation in buildings can be improved by staggering buildings to break the continuous street canyon structure

Table 3.
Natural ventilation prospects for the three different street configurations.

The three different configurations observed and shown in **Table 1** have *H/W* ratios of 0.48, 0.68 and 0.94, respectively. For the 0.48 streets, the street width is approximately 16 m and the average building heights is approximately 7 m. In

the case of the 0.68 streets, the street width is about 16 m and the average building heights is roughly 11 m. The 0.94 streets have street width of about 16 m and the average building heights is approximately 15 m. The schematics of the airflow regime for these streets are shown in **Table 2**.

From this study, it could be noted that the isolated roughness regime, which is the airflow that takes place between well-spaced buildings is not readily present in the urban streets of Enugu. From the schematic analysis above, the intermediate-wide street category only showed the potential to allow the continuous airflow from the urban boundary layer to the buildings, due to the lower heights of the buildings. This means that the speed of the airflow from the urban boundary layer is not disturbed at the windward face of the buildings, therefore permitting ventilated airflow. However, this potential is diminished by the presence of continuous often solid concrete fence walls with average heights of about 2.4 m (see **Figure 8**) which is often employed as security measures in buildings in this city. The other two categories in the Skimming flow regime are entirely dependent on airflow at the urban canopy layer which is the skimming airflow. This is due to the narrower street widths resultant from the building heights. Characteristics of skimming airflow include slower wind speeds and re-circulated airflow which lacks the speed for adequate permeability of natural ventilation in the buildings within these streets. The use of concrete fence walls is also rampant in this category of streets in Enugu which impedes further on the speed of the skimming flow. It is noteworthy however, that the orientation of a street, building elements (barriers) and prevalent wind directions ultimately affects the permeability of airflow for urban ventilation [8].

Table 3 presents the natural ventilation prospects in each of the three configurations shown above. With these scenarios, natural ventilation considerations could be carried along during the processes of building and urban street designs. However, the effectiveness of utilizing natural ventilation for different locations is improved through the orientation of streets and building planning.

6. Discussion and conclusion

A better understanding of the airflow and thermal characteristics within urban streets is paramount for developing urban area with energy saving considerations and human comfort. The rapid expansion of cities creates larger areas of increased drag, roughness and thermal forces that can significantly impact the flow patterns on regional scale. Hence, it is important to provide evaluation models with appropriate description of airflow, thermal conditions and natural ventilation models within tropical regions, as a function of meteorological frameworks that will accommodate predictions of airflow patterns on urban scales.

With climatic conditions prevalent in high temperatures and humidity, tropical cities like Enugu should aim towards the reduction of barriers and elements that impede on the airflow for natural ventilation. However, it is proper to reiterate that the major concern is with the comfort of occupants of the built environment. Similarly, identifying the criterion for judging the acceptable street climate conditions is a difficult task, as many objectives are involved. Assuming the major objective is for the airflow within street canyons, computations are available to calculate the effect of winds on the comfort and safety of humans in urban streets, for example see [34]. With knowledge of the general wind and temperature climatology and the effects of geometry, standard threshold of acceptable conditions can be predictable for any given location. However, the crucial objective is to establish airflow factors as a function of H/W in respect to natural ventilation within street canyons. Study identified the availability of wind tunnel and numerical models (as in [25, 35–37]) which can be applied with significant validation.

Through the analysis of the airflow regime for the three main street configurations in the tropical Enugu city, it could easily be concluded that the objective solution is to design streets with wider widths (i.e. smaller *H/W* ratios). A wider street provides better mixing of air and consequently better airflow in the urban street canyon. But this can never be the case in most modern city developments owing to land use objectives. Consequently, the other option is the provision of adequate openings between streets and courts and adopting different building heights in the streets which could improve air exchange within the urban canopy layer.

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