AN EVALUATION OF THE EFFECTS OF EXTERNAL LANDSCAPING ELEMENTS ON INDOOR AIRFLOW RATE AND PATTERNS USING COMPUTATIONAL FLUID DYNAMICS

Amos-Abanyie, S.
Koranteng, C.
Department of Architecture,
Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
Apeatse, K.E.
Department of Architecture,
Central University College (Miotso Campus), Accra, Ghana

Abstract

External landscape elements form an integral part of the built environmental design in enhancing both the performance and aesthetic values of buildings. The provision of landscape elements in the design and development of buildings can dampen the movement of air and as such affect air flow rate and patterns within buildings. The study focused on the characteristics of typical residential building in Ghana with climatic data of Accra. This paper is aimed at exploring, in systematic way, and by using Computational Fluid Dynamics (CFD) to model and simulate the effects of external landscaping elements on the internal airflow rates and pattern of buildings. The analysis of the simulated results of landscape elements at varying distances from a building were found to reduce indoor airflow rates by between 10% and 40%. Findings of this study are expected to inform building designers on impacts of external landscaping elements on indoor thermal comfort in relation to airflow rates and patterns, thereby serving as a basis for design decisions.

Keywords: External landscaping, fence wall, indoor airflow rate, comfort, Ghana

Introduction

The control of airflow is one of the most subtle and yet an inexpensive concern of the building designer. The primary aim of effective airflow is to make air movement assume patterns in buildings that satisfies and even delights the occupant (Roaf et al., 2007). Air flow merits a major consideration that control interactions among the physical elements of the building, its occupants, and the environment mainly because of its influence on heat and moisture content (Hutcheon, 1953). Effective air flow in a space can remove foul air, ensure personal thermal comfort (Richard, 2007), and expel moisture that can impact a materials long-term performance (Lstiburek, 2007). Air flow pattern within a building also affects its behaviour in the spread of smoke and other toxic gases, supply of oxygen in case of fire, indoor air quality, and thermal energy use.

The combined effect of high solar radiation and humidity levels in the warm-humid climate zones as that of Ghana makes continuous flow of air an imperative to achieve thermal comfort (Szokolay, 2004). Furthermore, psychometric analysis of the climatic condition of warm-humid parts of Ghana by Amos-Abanyie et al. (2009) revealed that cooling is required for an average of 81% of the time of the year. Amongst various passive cooling techniques to provide cooling, natural ventilation has a potential of an average of about 76% of the time of the year (Amos-Abanyie et al., 2009). However, the challenges in the design of buildings to run on natural ventilation in urban environments as that of Ghana can be very tricky as the densely developed neighbourhoods make it difficult to harness the full potential of prevailing winds.

External landscaping elements form an integral part of the built environment and contribute immensely to enhance passive performance of buildings. For instance, Bernatzky (1978) identified benefits of urban green structures as cooling hot air by evapo-transpiration, shading the ground and walls, reducing the radiant temperature, control of wind velocity and direction, filtering dust and noise.

Generally, there is limited knowledge and understanding about the effect of landscape elements on indoor air pattern and flow rates. Effects of several parameters as envelope, internal partitions, opening sizes and locations have been extensively investigated. Plants play several roles in providing an immediate practical value on a building's site. Besides affecting the absorptivity and emissivity of the Earth’s surface to reduce radiant temperature, by day, air is regenerated with oxygen into the atmosphere. Plants also enhance privacy, serve as wind break to control of wind velocity and direction, filter dust and noise, reduce glare from strong daylight, and solar radiation from entering and overheating buildings (Grondzik et al., 2010; Bernatzky, 1978). Grondzik et al. (2010) noted that unlike fixed-position sunscreens on buildings, plants provide their deepest shade in the hottest weather.

Aynsley (2007) asserts that in as much as density of trees can reduce local air temperatures by shielding the ground from solar radiation, cool air by evapo-transpiration and potentially reduce the dust content in air streams, they can also reduce the potential for natural ventilation when dense foliage obstructs wall openings intended to provide natural ventilation. Krishan et al., (1995) noted that wind speeds at 500 metres above ground level are fairly constant, however at heights closer to the ground, wind speeds are slowed down to varying degrees by the roughness at the ground surface and topographic features such as hills, ridges and escarpments posing marked influence on local wind speeds. A study by Heisler (1989) in flat suburban terrains affirms that large numbers of trees can significantly slow airflow near the ground. In environments where large trees form about 77% of ground cover, mean wind speeds at a height of 2 metres above ground can be reduced to about 24% of that at nearby airport. However, in flat suburban terrain without trees, mean wind speeds at 2 metres above ground level are approximately 78% of that at nearby airport.

External factors have an effect, either positively or negatively, on the airflow rates and patterns. Roaf et al. (2007) support this statement by drawing attention to the fact that external features can affect the impact of airflow on a building. They further highlight that wind breaks aside their conventional function of reducing the impact of airflow on a building can also increase humidity when air flowing through them pick up moisture reducing the temperature of the air. According to Richard (2007) airflow rates can be accelerated by up to 54% on the windward side of a hill due the effect of topography as an external factor on local wind speeds.

In accordance with Aynsley (2007) vegetation can also be used to modify external wind direction so as to enhance ventilation, as well as cool incoming air. Consequently, it is important to keep dense shrubs and tree canopies clear of windows and other air inlets to the building. Vegetation and for that matter trees cause pressure difference on sites and thus induces a increase or a decrease in air speed or direct airflow (Krishan et al., 1995). Vegetation can direct air flow into a building or deflect it away.

Moreover, careful placement of trees and hedges to create a narrowing path can direct and increase air speed (Krishan et al., 1995). Minor pressure differences are induced by placement of trees and hedges that marginally changes the air path. Air tends to shift towards the leeward of wind shadow where low pressure is induced. Conversely on the leeward or sheltered side of the hill the wind speeds near the ground are usually reduced and the wind direction changed (and even reversed if a re-circulating eddy is formed).

Szokolay (2004) noted that effective air movement in spaces accelerates convection, and also changes the skin and clothing surface heat transfer coefficient by reducing the surface resistance. Szokolay (2004) also observed subjective reactions to air movement at varying rates with 0.5m/s being pleasant, at 1.5 m/s being annoying. At overheated conditions however, air velocities of up to 2 m/s may be welcome.

In the design of buildings, the aesthetic demands of external landscaping elements mostly defy the effects they have on the buildings' passive performance such as natural airflow rates and patterns through the interior spaces. In the Ghanaian context, besides trees and shrubs, fence walls form one of the prominent features of landscaping elements. There has been extensive use of fence wall on boundary line of properties in response to the need for protection of the property and personal security of occupants and households. Besides frictional drag of vegetation and resistance, the obstructions that result from placement and dimensions of trees and fence walls can induce high and low pressure regions around buildings that could affect indoor air flow rates and patterns. Such effects are generally not considered in the design of the buildings and have not been evaluated in the Ghanaian context.

This study is aimed at evaluating the influence of surrounding landscaping elements of a building on internal air flow rate and pattern. It is expected that findings of this study will guide designers to make informed decisions regarding the choice and placement of external landscaping elements to direct air movement to contribute to indoor thermal conditions in residential buildings in Ghana.

Materials and methods

Many tools are available for building professionals to model natural ventilation performance. Among them, Computational Fluid Dynamics (CFD) programs are becoming more readily available. They can produce graphical results that aid users to visualize and understand the "real" phenomena by including information on flow vectors, particle tracking, air velocity and temperature profiles (Clarke, 1993). This study adopted computer based modelling and simulation analysis technique using the WinAir software as a CFD tool to investigate the effects of fence walls and tree types on indoor air flow rates and patterns. Data was exported to and from WinAir using Autodesk® Ecotect Analysis software (Ecotect). The following sections discuss the procedures employed in the model development, simulations and analysis of the results.

Model Description

A standard model of a bedsitter configuration was modelled and used as a Base Case, referred to as BC, for the simulations. There was no interior furniture arrangement as their effects were assumed negligible for this study. No recessions or egresses were introduced to eliminate any wing-wall effects after Chungloo and Tienchutima (2011). Liping *et al*. (2007) established that naturally ventilated residential buildings in hot-humid climates can have window to floor ratios ranging between 10% and 40%. Moreover, with an optimum ratio of 24% was stipulated to address the conflict daylighting provision has with solar penetration for improved indoor thermal comfort. For this study, a window to floor ratio of 19% was adopted based on the dimensions of modules available on the market. Windows (ventilation openings) were placed in external walls opposite each other to ensure a continuous breeze path between the ventilation openings. Figures 1 and 2 show the layout and 3D view of the model. Each unit has a floor area of 32.9 m^2, comprising of a living room, washroom, kitchenette and a porch. It was modelled as a stand-alone building for the simulation.

Simulations of the base case were carried out to establish air flow rates and patterns (Figures 1and 2) with no external landscaping elements around the building. The affects on air flow rate and pattern in the interior spaces were investigated using six test cases obtained by variations in types and distances from the model of fence wall and trees (see Table 1). The effects of fence wall and tree were tested at two positions. The fence walls were first tested at a horizontal distance of 3.0 metres from the wall of the model, and then at 1.5 metres. The tree was first tested at a distance of 5.8 metres equivalent to twice its height, and then at a distance of 2.9 metres.

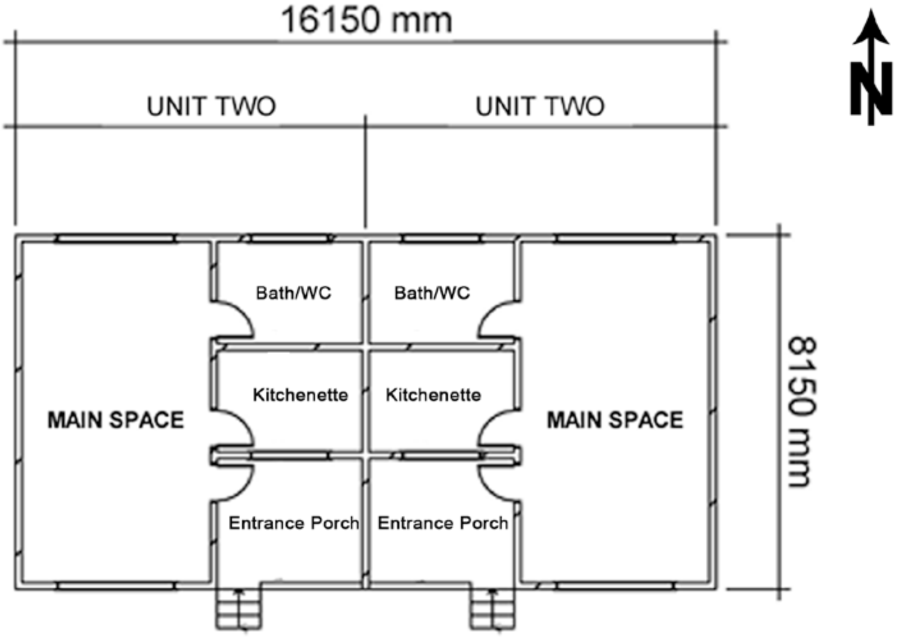

Figure 1: Plan of the simulated bedsitter

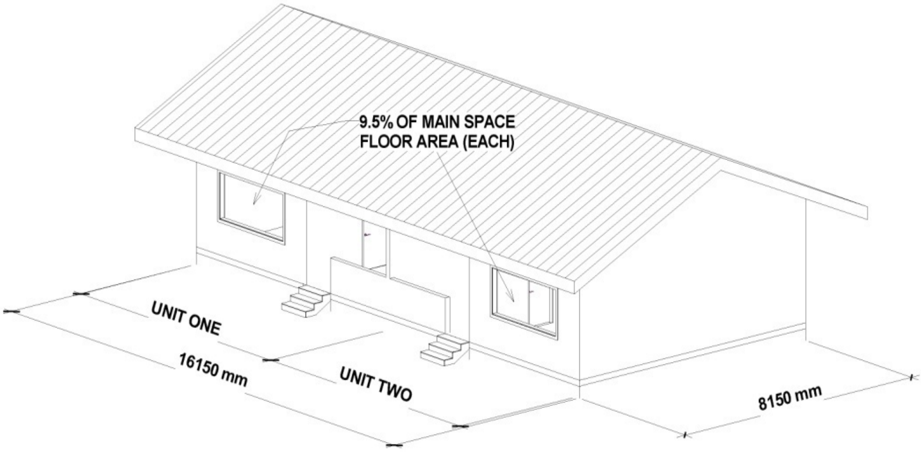

Figure 2: Standard model of simulated bedsitter

Table 1: Characteristics of models simulated

	LANDSCAPE ELEMENTS	HEIGHT (MM)	DISTANCE FROM BUILDING (MM)
Base Case Model	BC	-	-
Solid Fence Wall	SOLID WALL @ 3.0m	1800	3000
	SOLID WALL @ 1.5m	900	1500
Perforated Fence Wall	PERFORATED WALL @ 3.0m	1800	3000
	PERFORATED WALL @ 1.5m	900	1500
Tree	TREE @ 5.8m	4000	5800
	TREE @ 2.9m	2000	2900

Table 2: Export Settings from Ecotect to WinAir

Parameter	Boundaries
Wind Settings	Speed = 12.15m/s
	Direction = 45
	Air Viscosity = default (1.8e-05)
	Air Density = default (1.2 kg/m^3)
Monitoring Cell	X Position = 0
	Y Position = 0
	Z Position = 0
Conditions	External Contaminant = default (0)
WinAir Control File	No. Iterations = default (500)
	Save Interval = default (100)

Simulation Procedure

WinAir exports setting from Ecotect used for the simulation are shown in Table 2. A weather data of Accra was used for the simulations. Accra experiences highest average wind speed of 5m/s occurring around August 21, at which the average daily maximum wind speed is 8m/s. However, around December 4, a lowest average of 3m/s is experienced

(Weather Spark, 2013). For this study, a mean outdoor wind speed of 4m/s blowing from southwest direction was used. The predominant directions of the wind on a daily basis are from the southwest and northeast. Despite their different orientations, the prevailing winds from the two directions can be simulated as one case, since they come from the exact opposite directions (Tanstasavasdi et al., 2001).

Analysis

It should be noted that three dimensional (3D) models provide more accurate results since air flow is three dimensional (Lam et al., 2006). However, to reduce the complexity of the computation and analysis, only two-dimensional (2D) models were used. Velocity profile maps based on a 1m grid centre was prepared for the main space of the bedsitter for each type of landscape element (Table 1). For the analysis, velocities between 0.5 to 2.0 m above floor were considered. This is the range for which most human activities as seated positions in a sofa, chair and desk, lying in bed, and standing fall within (Gut and Ackerknecht, 1993). Velocities were expressed as a dimensionless ratio: U_L/U_{NL}, where U_L is the velocity at a given point on the profile with a landscape element in place; and U_{NL} the velocity at a corresponding point without a landscape element in place (Olgyay and Olgyay, 1963).

Results and discussion

The simulated section flow vector, air flow rate, and plan flow vector of the model with no landscaping elements around it are presented in Figures 3, 4 and 5. The simulations were carried out with wind from the south-western direction of the models, thus for the discussion of the results, the window in the southern wall is the inlet window and the window in the northern wall is the outlet window. Wind speed and pattern within unit 2 of the model was used for the analysis. Figure 3 indicates a slowdown of an air stream and pile up on approach at the inlet window, inducing a relatively higher air pressure. At a height of approximately 1.8m above the ground, average wind speeds attained a mean of approximately 2.13 m/s.

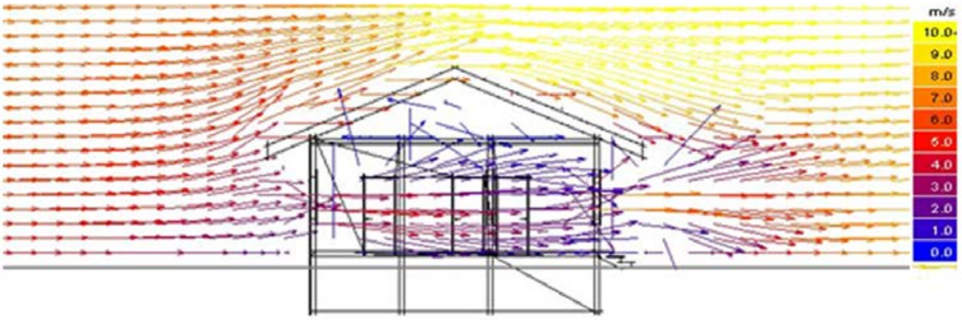

Figure 3: Section flow vector of model with no landscaping elements

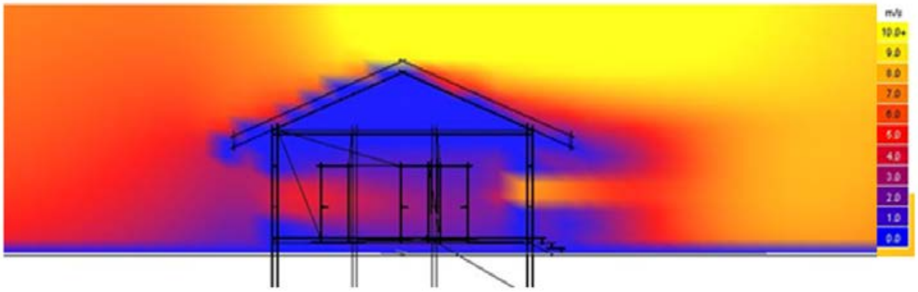

Figure 4: Section air flow rate of model with no landscaping elements

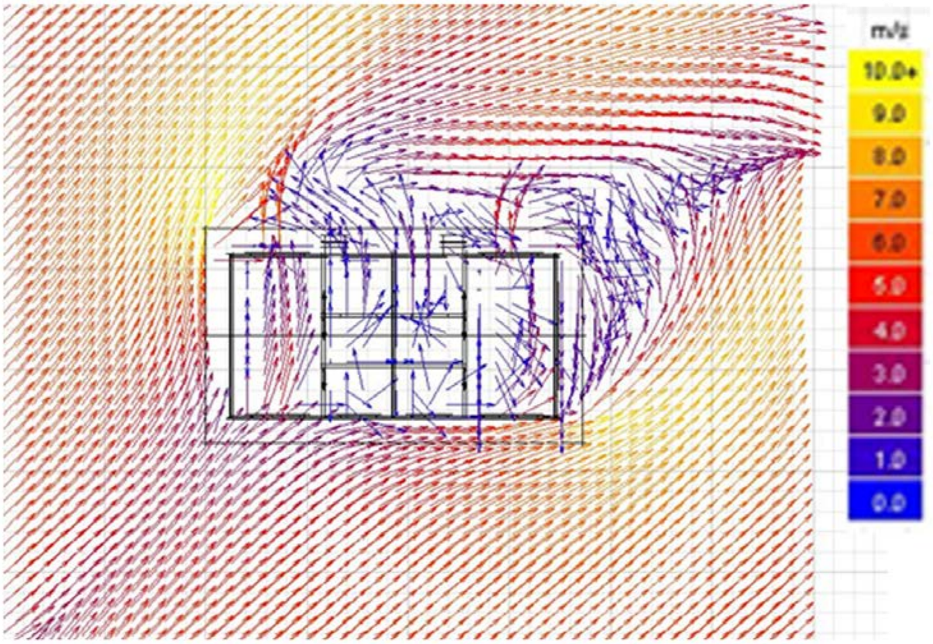

Figure 5: Plan flow vector of model with no landscaping elements

While low pressure areas were induced on the sides adjacent to the windward face, a wind shadow with a relatively low pressure is induced on the leeward side, as seen in Figure 5. Away from the leeward surface of the building, and at a distance of approximately 8.4 meters, or 1.5 times the height of the building, the air is at rest. It can be appreciated that the air flow patterns created around the building have been determined purely by its geometry, with no such influence by the landscaping elements. The results show that the wind at the leeward side of the inlet window had an average velocity of 2.36m/s. There is a general movement from the inlet to the outlet window with flow rates in a decreasing fashion. The pressure differences on the inlet and outlet windows contributed to air flow rates and patterns within the space, achieving rates of 2.43 m/s at a distance of 1meter leeward of the inlet window and 2.04 m/s at a distance of 10m leeward of the inlet window.

Higher wind velocities were achieved when the air stream changed direction within the space on encountering the eastern wall at 45° after entering the inlet window. As can be appreciated from Figure 5, on encountering the eastern wall from the south-western direction, the speed of the wind is enhanced to relatively higher levels. This is in conformity with findings by Givoni (1976) on effect of window location and wind direction on average air velocity, where winds in oblique direction had relatively high speeds compared to external wind speeds. Mean indoor wind velocities between 0.5 to 2.0 meters above indoor floor level was analysed. The effects of walls and trees on the indoor air flow rate and patterns are discussed in the following sections.

Effect of fence wall

In assessing the effect of the fence wall, four scenarios were considered; each of solid fence wall and perforated fence walls were considered at 3m and 1.5 m away from the model. In the scenario with the solid walls, air currents on approach are first diverted upwards by the wall and then swept to the ground, with an area of relative calm being created near the ground as also observed by Krishan et al., (1995), and presented in Figure 6.

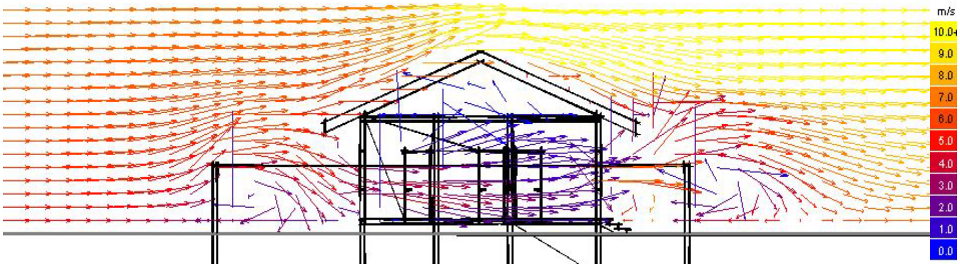

Figure 6: Section flow vector of model with solid fence wall at 3m away

The region close to the ground on the leeward side of the fence wall experienced the nost protection. Eddy currents induced over the wall, however, reduced the area of protection as explained for solid barriers by Olgyay and Olgyay (1963). At points further away from the fence wall towards the model, there is more exposure up to a point where air currents reach full velocity of about 1.75m/s. With the perforated wall, at 3m from model, inlet window has little protection. This could be attributed to the openness of the wall resulting in a smaller protected area.

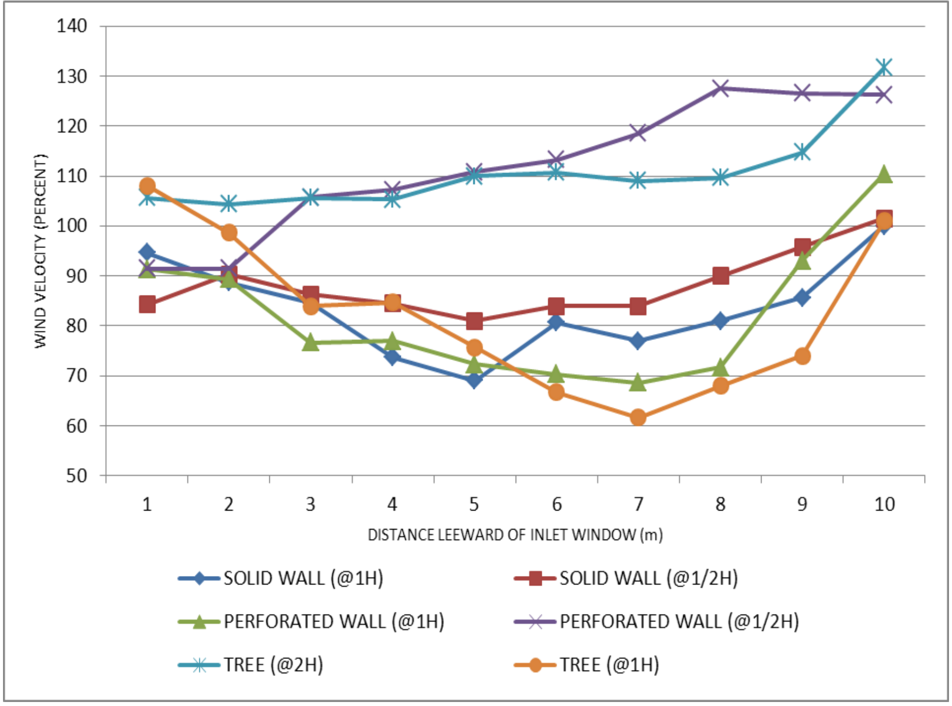

Figure 7: Wind velocity reduction profile by landscape elements

The solid and the perforated walls at 3m induced an average wind velocity of 1.98 m/s and 2.16m/s respectively at the windward end of the inlet window. As can be seen in Figure 7, at heights of between 0.5 to 2.0 meters above indoor floor level, the solid walls maintained an indoor velocity ratio of 95% and dropped to a low of 69%, or a reduction of 31% of indoor air velocity, at 5m leeward of the inlet window. The velocity then rose gradually up to 100% velocity ratio at 10m leeward of the inlet window (Figure 7).

The wind velocity of the perforated wall at 3m, even though had a higher mean wind velocity windward of the inlet window, dropped from about 91% velocity ratio on exiting the inlet window and maintained a lowest of 69%, or a reduction of 31% of indoor air velocity, occurring after

7m leeward of the inlet. Indoor wind velocity rose sharply to achieve 100% on exit of outlet window (Figure 7).

In the scenarios with fence walls at 1.5m from the model, the solid wall and perforated wall respectively induced an average wind velocity of 2.12.m/s and 2.41m/s at the windward end of the inlet window. The solid wall at 1.5m achieved a wind velocity ratio of 84% on entry of the inlet window, and gradually reduced to a minimum of 80%, or a reduction of 20% of indoor air velocity, at 5m leeward of the inlet window. Velocity ratio then rose to attain a maximum of 101% on exit of the outlet window. The perforated wall, however, achieved a wind velocity ratio of 92% on entry through the inlet window, and gradually reduced to a minimum of 90%, or a reduction of 9% of indoor air velocity, just at 2m leeward of the inlet window. Velocity ratio then rose to attain a maximum of 126% on exit of the outlet window.

For both solid and perforated fence walls, the closer they are to the models, the lower are the velocity ratios. In such instances, the potential of wall openings intended for natural ventilation are reduced as a result of obstruction (Ansley, 2007).

Effect of trees

In the scenarios of the trees, the foliage mass in both cases resulted in the passage of air currents being blocked and diverted downward of the foliage towards the inlet window (Figures 8 and 9). The above was explained by Krishan et al (1995) as resulting from the difference in pressure induced on the windward and the leeward ends resulted in marginal changes in the direction of air.

Trees at distances of 5.8metres and 2.9metres from the model induced an average wind velocity of 1.59m/s and 1.15m/s respectively at the inlet window. Although there were reduced wind speeds, they were still above the prescribed range by Szokolay (2004) as being pleasant. Moreover, in overheated conditions resulting from the combined effect of high solar radiation and humidity levels experienced in the warm-humid climates, velocities of up to 2m/s may be welcome. The tree at a distance of 5.8metres achieved a mean velocity 106% on exit of inlet window and maintained a general increase to achieve a high of 132%, or an increase of 32% of indoor air velocity, at 10m leeward of the inlet window (Figure 7). Richard (2007) affirms that air flow can be accelerated by up to 54% on the windward side due to the effect of an external factor on local wind speeds.

However, the tree at a height of 2.9metres achieved a velocity ratio of 108% and experienced a fall in velocity ratio to a lowest of 61%, or a reduction of 39% of indoor air velocity, occurring at a distance of 7m leeward of the inlet window. Indoor mean velocity then rose sharply to maintain a high of 100% at a distance of 10m leeward of the inlet window (Figure 7). The mean indoor air velocity ratios of Test Models are presented in Table 3.

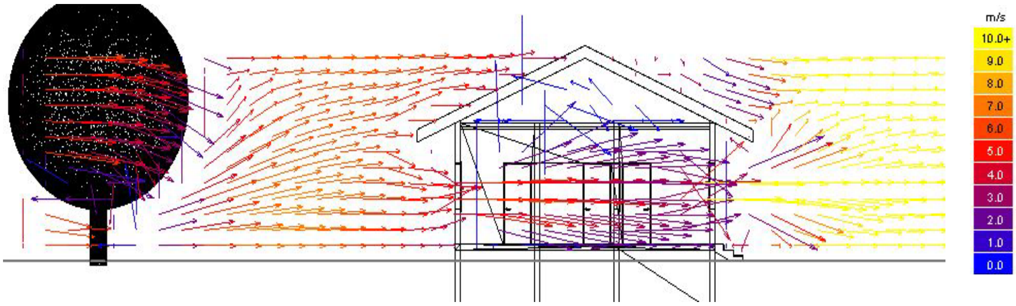

Figure 8: Section flow vector of model with tree at 5.8m away

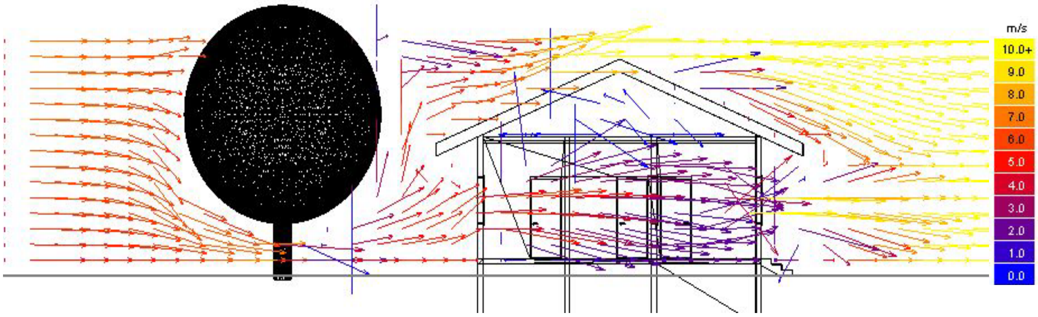

Figure 9: Section flow vector of model with tree at 2.9m away

Table 3: Mean indoor wind velocity ratios of Test Models

Model	Mean wind velocity ratio windward of inlet window (%)	Minimum mean wind velocity ratio (%)	Distance of mean minimum velocity ratio leeward of inlet window (m)	Mean wind velocity ratio windward of inlet window (%)
SOLID WALL (@ 3.0m)	95	69	5.0	100
SOLID WALL (@ 1.5m)	84	80	5.0	101
PERFORATED WALL (@ 3.0m)	91	69	7.0	100
PERFORATED WALL (@ 1.5m)	92	90	2.0	126
TREE (@ 5.8m)	106	104	1.5	132
TREE (@ 2.9m)	108	61	7.0	100

Conclusion

The study sought to evaluate the effects of use of fence wall and trees as landscape features on indoor air flow rate and patterns. The study employed a systematic approach employing Computational Fluid Dynamics (CFD) to simulate the effects of external landscaping elements on the internal airflow rates and pattern of buildings. The findings of the study confirm earlier studies that the type and placement of landscape elements can affect indoor air flow rates and patterns. Generally, air currents on entry through the inlet window experience a reduction in flow rates as it proceeds into the space. However, on approach to the wall with the outlet window, an obstruction is created that induces a relatively higher pressure zone and thus increases the flow rate. The reduction in the flow rate were found to be between10% and 40% that of the scenario with no landscape elements.

Considering the warm-humid climatic condition of the context of this study that requires continuous and unobstructed flow of air in attaining thermal comfort, it can be appreciated from the findings that fence designs should be made to allow free flow of air. The findings also suggest that in spite of the several advantages of vegetation as landscape elements in enhancing the microclimatic conditions, their placement in proximity to openings can significantly affect indoor air flow either positively or negatively.

The authors recommend that a much more comprehensive study be carried out considering various window types and associated accessories and interior furniture arrangement.

References:

Amos-Abanyie, S., Akuffo, F.O., **Victor Quagrain, V., (2009) "**Unveiling Energy Saving Techniques for Cooling in Residential Buildings in Ghana." International Journal of Ventilation, Vol. 8, Issue 1, Coventry, UK, pg. 23-35

Aynsley, R. (2007). Natural Ventilation in Passive Design. BEDP Environment Design Guide. The Royal Australian Institute of Architects.

Bernatzsky, A. (1978). Atmospheric Ecology and Preservation. Elsevier, Amsterdam.

Clarke, J.A. (1993) Assessing building performance by simulation. *Building and Environment*, 28 (4), 419-427.

Givoni, B. (1976). *Man, Climate and Architecture*, Applied Science Publishers, 2nd Edition, London.

Grondzik, W. T., Kwok, A. G., Stein, B. and Reynolds, J.S. (2010). Mechanical and Electrical Equipment for Buildings, Eleventh Editon. John Wiley & Sons, Inc. New Jersey.

Gut, P. and Ackerknecht, D. (1993) "Climate Responsive Building; Appropriate Building Construction in Tropical and Subtropical Regions". SKAT, Switzerland. 1993 pp. 37-50

Heisler, G. (1990). Mean wind speed below building height in residential neighbourhoods with different tree densities. *ASHRAE Transactions , Vol. 96, No.*

Hutcheon, N.B. (1953) Fundamental Considerations in the Design of Exterior Walls for Buildings, Engineering Journal, Vol. 36, No. 1, pp. 687-698.

Koranteng, C. (2011). The Thermal Performance of an Educational Office Building in Ghana, Journal of Applied Science and Research, Vol. 3, 4: 222-232.

Krishan, A., Jain, K., Rajgopalon, M. and Yewari, P. (1995). Shelter of form: the "process of design" in question, Proceedings of the Climatically Responsive Energy Efficient Architecture, PLEA 98 International Conference, A design Handbook. Vol.1: Basic Principles and Elements. Passive Low Energy Architecture International, New Delhi, 1995.

Lam, K. P., Kim, S. H., Satwiko, S. Jennings, J. and Cole, J (2006). Assessment of the Effects of Environmental Factors on Air Flow in and Around Buildings. PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006

Liping, W., Hien,W.N & Shuo, L. (2007). Facade Design Optimization for Naturally Ventilated Residential Buildings in Singapore. Energy and Buildings, 39 (8): 954-961.

Lstiburek, J. W. (2007). A Toward an Understanding and Prediction of Air Flow in Buildings. An unpublished PhD thesis submitted to the School of Graduate Studies, University of Toronto

Olgyay, V. and Olgyay (1963). Design with Climate – Bioclimatic Approach to Architectural Regionalism. Princeton University Press, Princeton, New Jersey

Richard, A. (2007, May). Natural Ventilation in Passive Design. *Environment Design Guide* .

Roaf, S., Fuentes, M. and Thomas, S. (2007). *Ecohouse: A Design Guide* (3rd Edition ed.). Elsevier, Oxford, UK

Szokolay, S. V. (2004). Introduction to architectural science - the basis of sustainable design. Elsevier Science. Oxford.

Tanstasavasdi, C., Srebic, J. and Chen, Q. (2001). "Natural ventilation design for houses in Thailand", Energy and Building, 33(8), 815-824

Weather Data: *U.S. Department of Energy*. (2012, July 17). Retrieved March 1, 2013, from U.S. Department of Energy Web site: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=1_africa_wmo_region_1/country=GHA/cname=Ghana