EFFECT OF BUILDING PLAN FORM ON HUMAN THERMAL COMFORT IN NATURALLY VENTILATED OPEN-PLAN ENCLOSURES LOCATED IN HOT CLIMATES

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ABSTRACT

This study aims to examine the effect of building plan form on internal thermal comfort conditions in naturally ventilated open-plan buildings located in hot climates. The study examined the square and the rectangular plan forms in relation to several values of wind direction, building plan depth, and climatic conditions. The study utilised CFD for ventilation prediction, DesignBuilder for thermal modelling, and the Tropical Summer Index (TSI) for thermal comfort assessment. These three tools were integrated in a quantitative approach to fulfil the study aim. The study concluded that the use of area-weighted average velocity magnitude is more accurate in the assessment of natural ventilation performance, as it accounts for both internal velocity magnitude and distribution. The study confirmed the common observation that the use of shallow building plans is more effective to increase internal air velocity and improve internal thermal comfort. At some point of increased plan depth, the internal air velocity magnitude dramatically decreases. In the three examined wind directions, this occurred when the plan depth exceeded 3H in the square cases and 2.5H in the rectangular ones, where H is the building height. This value is much less than the commonly recommended maximum value of 5H. The study also concluded that reducing building depth in the square cases has generally more potential to improve thermal comfort conditions when compared with the rectangular cases. The gross increase in Percentage of People Comfortable, PPC, in all the examined cases was 23% in the square cases, compared to 11% in the rectangular cases.

KEYWORDS:

natural ventilation, buildings, open-plan, thermal comfort, hot climate.

INTRODUCTION

Researchers face the challenge of introducing solutions that increase the dependency of buildings on sustainable resources of energy. This is essential to reduce and possibly replace the reliance on rapidly depleting fossil fuel resources. Natural ventilation as a passive cooling technique has a great potential in this regard. Natural ventilation is purpose-provided ventilation, as opposed to air infiltration. Natural ventilation occurs through building apertures such as windows, ventilators, shafts, etc., and can usually be controlled by the occupant. It has two

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main objectives: to control air quality, and to provide passive cooling or heating. It relies on two natural driving forces, which are either the stack effect due to the difference in air temperature, or the wind effect due to the difference in air pressure. A combination of both effects is also possible. The use of natural ventilation in buildings has many advantages—the main one being that a fossil fuel free mechanism requires low construction and operation cost and minimum maintenance. As a general rule of thumb, naturally-ventilated buildings are 40% less in operation energy cost when compared to mechanically-ventilated buildings (CIBSE, 1997). However, there are some disadvantages which cannot be ignored, especially the random nature of wind (Asfour, 2015).

Natural ventilation is a commonly used passive cooling strategy. It is used to cool down indoor air, internal building surfaces, and the occupants as well. There is a direct relationship between natural ventilation and thermal comfort. Natural ventilation encourages heat transfer between the human body and its ambient environment. In this context, thermal comfort may be defined as "that condition of mind which expresses satisfaction with the thermal environment" (BSI, 2005). Thermal comfort relies on several personal and environmental factors. Among these factors, the role of air speed is significant. This is mainly because the skin loses heat by convection when fresh cold air passes over it. When the outdoor air temperature is less than the indoor temperature, airflow through a building removes undesired internal heat gains and increases thermal comfort. If the outdoor air temperature is higher than the indoor temperature, it has to be reduced by some techniques such as night-time ventilation (Moore, 1993). In hot arid regions, natural ventilation works effectively when integrated with an evaporative cooling system. In general, cross ventilation is more effective than single-sided ventilation. CIBSE (1997) mentioned that cross ventilation is effective up to a maximum depth that equals five times the space height, i.e. an aspect ratio of 5. Karava *et al.* (2011) carried out a parametric airflow assessment in some cross-ventilated buildings. The study focused on a single-zone building model tested in a wind tunnel under isothermal flow conditions. It found that airflow patterns in such cases have a complex pattern. Inlet-to-outlet ratio, relative location of openings, and wall porosity are found to be important parameters that should be considered in airflow assessment. Existence of internal partitions and obstacles is another factor, which leads to airflow rate overestimation when neglected (Chu and Chiang, 2013). Also, wind direction is an important factor. In real conditions, wind direction varies constantly. Thus, it is important to consider this fluctuation in any natural ventilation simulation (Ji *et al.*, 2011).

Several tools are used to predict ventilation performance in buildings. This includes analytical models, empirical models, small-scale experimental models, full-scale experimental models, multi-zone network models, zonal models, and Computational Fluid Dynamics (CFD) models. The CFD models are the most popular, especially when coupled with other models (Chen, 2009). In the context of the current study, it is common practice to use CFD in order to investigate the effect of different architectural design parameters on natural ventilation performance. For example, Kindangen *et al.* (1997) performed a CFD analysis of ten roof shapes to study their impact on wind-induced natural ventilation. The average indoor velocity coefficient was used as an indicator of wind-induced ventilation performance. Meroney *et al.* (1999) carried out a wind-tunnel and numerical modelling of airflow considering several building shapes. These shapes included two rectangular prisms and a cubical building. Calculations were carried out using CFD in addition to wind-tunnel measurements to visualise the resulting airflow patterns and calculate pressure coefficients. Although this study offered good validation data, it did not show the geometrical advantages of each model in terms of natural ventilation performance.

In a related study, Chu and Chiang (2014) investigated wind-driven cross ventilation in deep buildings. The main aim was to examine the rule of thumb for effective wind-driven cross ventilation, which suggests that the building depth D should be less than five times of ceiling height H. They investigated several cubic cases with different aspect ratios (D/H = 1.25, 2.5, 5.0 and 8.0). In these cases, building length was assumed fixed at 10 m, building depth was varied, and one large inlet and outlet were used at windward and leeward, respectively. CFD simulation (LES model) was used to estimate the pressure coefficient and velocity vectors (presented at the central vertical section). The results revealed that the ventilation rate decreases as the building depth increases. One reason is internal friction, which can produce a stagnant zone with low wind speed inside the building. The other reason is due to the fact that the pressure difference between the windward and leeward façades of deep buildings (aspect ratio D/H ≥ 2.5) is smaller than that of a short building (D/H = 1.25). As a result, the ventilation rate decreased as the building depth increased, however, the ventilation rate drastically decreased only when the building aspect ratio D/H exceeded 1.25. After that, the ventilation rate decreases slightly and uniformly. However, this study did not examine the effect of wind angle, the effect of literal openings, internal air velocity distribution at users' level, and the resulting effect on thermal comfort.

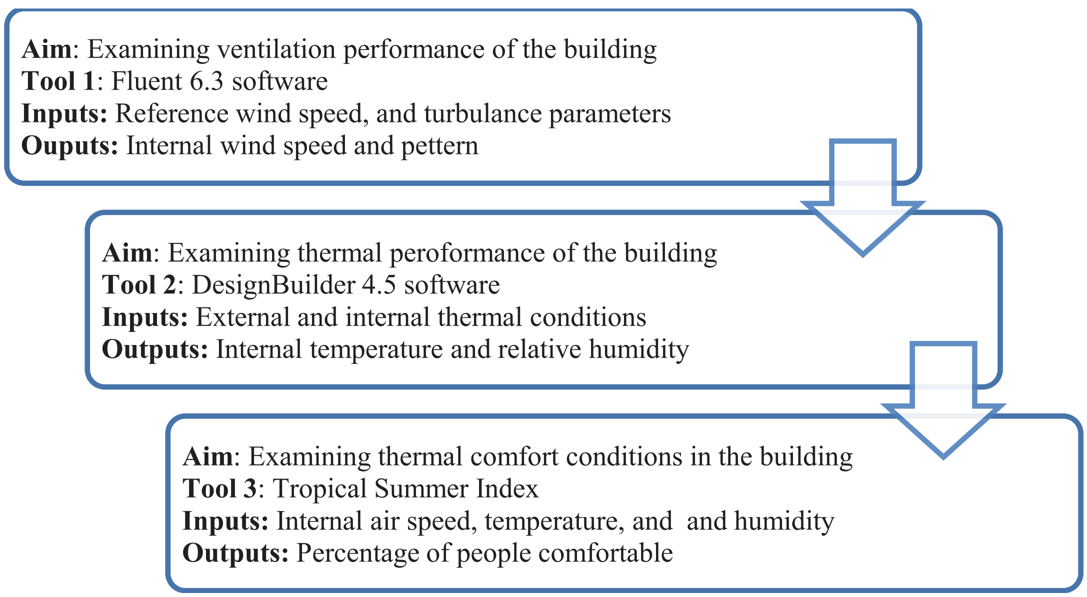
The relationship between natural ventilation and thermal comfort, on the other hand, was the subject of several studies as well. Wong *et al.* (2003) carried out natural ventilation and thermal comfort investigation in a commercial centre in Singapore. Natural ventilation performance was assessed depending on the magnitude of wind speed using wind tunnel measurements. In addition, a thermal comfort survey was conducted to specify areas with poor thermal comfort conditions. Several measures to improve natural ventilation performance and thermal comfort conditions were assessed, such as increasing the width of the centre passageway, providing openings in the roof, and increasing the roof height. Prajongsan and Sharples (2012) analysed high-rise residential buildings in Bangkok to examine enhancing natural ventilation and thermal comfort through the use of ventilation shafts. This was done considering 12 different wind conditions (six wind speeds and two wind directions). CFD analysis revealed that a ventilation shaft located at the rear of a room can greatly increase the pressure difference across the room, which increases internal air velocity magnitude. The comfort hours during summer were calculated based on the room's operative temperature and using Szokolay's model of physiological cooling. Results showed a significant improvement in thermal comfort by employing the proposed ventilation shaft.

Thus, the main aim of this study is to explore the effect of building form and wind direction on natural ventilation performance while also considering the effect of this performance on internal thermal comfort conditions. This has been done through parametrical simulation of several cases that represent open-plan large enclosures. In these cases, cross ventilation is employed for passive cooling under hot climatic conditions. To achieve this aim, a mixed qualitative and quantitative approach has been adopted, in which CFD, DesignBuilder and the Tropical Summer Index (TSI) have been used as research tools. This is further explained in the following section.

METHODOLOGY

The study methodology is based on a comparative analysis of several hypothetical modelling cases. CFD, DesignBuilder and TSI have been used as research tools to produce a bulk of data and illustrations that have been qualitatively and quantitatively analysed. These cases have been simulated using Fluent 6.3 software to examine natural ventilation performance. Then, DesignBuilder 4.5 has been used to find out the internal air temperature in these cases during the summer. Outputs of DesignBuilder 4.5 software have been used in TSI to find out the effect of the modelled internal air velocity magnitude (the independent variable) associated with air temperature and relative humidity on human thermal comfort (the dependant variable). This is further explained in the following sections.

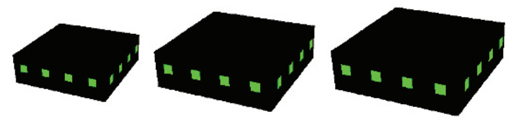
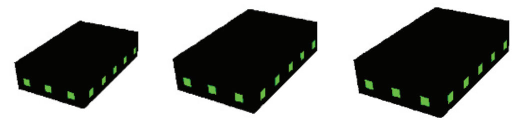
FIGURE 1. Workflow of the modelling study.



Geometrical parameters

Different hypothetical three-dimensional cases have been assumed to investigate the research problem. These cases are assumed to be open-plan cases to represent relatively large non-domestic enclosures such as office buildings. In general, natural ventilation is an effective strategy for improving thermal comfort conditions in open spaces (Capeluto, 2005). This is mainly due to the limited use of internal partitions, which form a main obstacle against air current movement. Two commonly used plan forms have been selected: the square and the rectangular plan form. Three plan areas for each form were investigated. Area selection was based on a CIBSE recommendation that for effective cross ventilation in non-domestic buildings, plan depth should not exceed five times the space height (CIBSE, 1997). Space height, H, is assumed to be 5m in this study. Based on this recommendation, three square cases S1, S2, and S3 with a length of 3, 4, and 5 H are assumed respectively. In the rectangular cases, an equivalent area is provided for each case considering an aspect ratio of 1:1.5. Windows are provided at all building walls with an area equal to 10% of the building plan area. Ambient wind speed is assumed 3 m/s. Each case has been modelled in three wind directions: parallel (0°), oblique (45°), and perpendicular (90°) direction. Each case has been assigned a unique code to show: the plan form (S for square, and R for rectangular cases), followed by building depth (1, 2, or 3), followed finally by wind direction. Table 1 shows the proposed modelling cases.

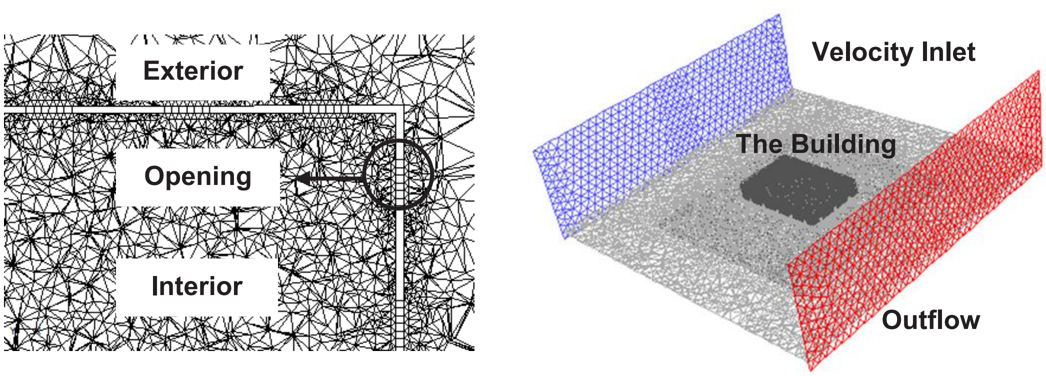
TABLE 1. Geometrical characteristics of the cases examined in the study.

Plan Form	Height (H)	Case Code	Dimensions	Illustration
Square	5 m	S1	3H * 3H	
		S2	4H * 4H	
		S3	5H * 5H	
Rectangular	5 m	R1	2.5H * 3.7H	
		R2	3.3H * 4.9H	
		R3	4.1H * 6.1H	

Computational Fluid Dynamics (CFD)

CFD modelling has been used as a main research tool in this study to simulate the wind environment inside and around the examined cases. Despite the relatively sophisticated nature of this tool, it is practical for parametric studies, and is considered as a powerful flow simulation tool for both ventilation and heat transfer. Firstly, Gambit 2.2 software was used to three-dimensionally draw the solution domain, define its boundary conditions (velocity-inlet and outflow), and generate the solution mesh. Domain size and mesh characteristics for the different cases are shown in Table 2. In general, a compromise is required between solution accuracy and processing time. Finer meshes increase processing time and may go beyond the available processors ability. To overcome this challenge, a hierarchy in mesh size was implemented to keep mesh size reasonable and provide fine mesh at the building interior (Figure 2).

FIGURE 2. Mesh hierarchy and boundary conditions in the solution domain.



To enable this hierarchy, a tetrahedral mesh scheme was implemented at the solution domain. Extra care was given to the mesh of building openings, where the airflow rate is recorded. Thus, hex-map mesh was used in building openings with a size of 0.2 m. Appropriate domain size that prevent reversed flows and lead to solution convergence was examined for each case by trial and error. In the case of 0° and 90° wind directions, a domain depth that equals 3.75 times the length of the longest side of the building was found to be appropriate. In the case of oblique wind directions, this equals 6 times the length of the longest side of the building. A domain height of 20 m was used in all cases.

TABLE 2. Domain size and mesh characteristics, and the resulting area-weighted average internal wind velocity for the different modelling cases.

Wind direction	Case Code	Mesh Volume (cell)	Domain Dimensions (m)	Average Internal Velocity (m/s)
0°	S1-0	300,000	56* 56*20	0.43
	S2-0	350,000	75*75*20	0.36
	S3-0	480,000	94* 94*20	0.38
	R1-0	250,000	14*14*20	0.49
	R2-0	425,000	92*92*20	0.40
	R3-0	460,000	115*115*20	0.39
90°	S1-90	300,000	56*56*20	0.43
	S2-90	350,000	75*75*20	0.36
	S3-90	480,000	94* 94*20	0.38
	R1-90	250,000	14*14*20	0.36
	R2-90	410,000	92*92*20	0.35
	R3-90	470,000	115*115*20	0.37
45°	S1-45	400,000	90*90*20	0.51
	S2-45	460,000	120*120*20	0.44
	S3-45	300,000	150*150*20	0.47
	R1-45	360,000	110*110*20	0.51
	R2-45	480,000	147*147*20	0.42
	R3-45	370,000	184*184*20	0.45

Fluent 6.3 software has then been used for numerical data processing depending on the imported solution mesh. This is based on the finite volume numerical solution of the Navier–Stokes equations. Most airflow problems in buildings consider airflow to be turbulent, thus a correct definition of the turbulent model is required to solve the transport equations. The standard k-e model was implemented in this study, which is commonly used in simulating buildings, where the wind environment is highly turbulent. It is believed to be among the most used and developed turbulence model that could predict airflow rate (Awbi, 2003) (Shen *et al.*, 2012). This model is based on two separate transport equations that are used to determine the turbulent kinetic energy (k), and its dissipation rate (*e*) (Fluent Inc., 2006). In the derivation of this model, the flow is assumed to be fully turbulent. To implement this model, it is

required to specify the turbulence parameters. There are several methods in this regard including turbulence intensity and length scale. The length scale simply equals 0.07L, where L is the inlet height. The turbulence intensity is dependent on the domain size and Reynolds number. Thus, a turbulence intensity of 5% in the normal wind and 10% in the oblique wind have been assumed (due to increasing solution domain size in the latter case). For the same domain size, a fixed value of turbulence intensity was used. Finally, a residual sum of 10^{-6} for convergence was assumed. Considering the assumed hot climatic conditions in this study, ventilation is mainly induced due to wind pressure difference, with a limited effect of natural convection. This is because of the relatively lower difference between indoor and outdoor temperatures (Chow, 2004). Therefore, energy settings have been set off in this study, which excludes the effect of solar radiation and natural convection.

As for code verification, extensive work has been done so far by researchers in the field of building ventilation to compare CFD results with experimental results, usually wind tunnel tests. CFD and experimental methods have been usually reported to show good agreement (Stavrakakis, 2008), (Hussain, and Oosthuizen, 2013), (Shetabivash, 2015). However, verification is recommended regarding the implemented CFD code to ensure that the software is implemented correctly. The implemented CFD code in this study was verified in a previous validation study (Asfour, 2007). The validation was based on the estimation of airflow rate using mathematical and CFD models. The Network mathematical model was chosen in this instance since it has the advantage of analysing multipath airflows in naturally-ventilated buildings. Several three-dimensional square and rectangular building models were considered in the validation process. Room dimensions were 5*5 and 8*4 m for the square and rectangular cases, respectively. The following parameters were assumed fixed: room volume, opening area, opening configuration, and ambient wind speed. Airflow rate induced by wind pressure difference in these cases was estimated using the following equations:

$$Q_n = A_{\text{eff}}\sqrt{(2\Delta p/\rho)} \tag{1}$$

Where Q_n is airflow rate through an opening n (m^3/s), A_{eff} is the effective opening area, ΔP is pressure difference (Pa), and r is air density (kg/m^3). Pressure difference across the opening can be estimated using the following equation:

$$\Delta P = 0.5\rho V^2\left|\left(C_{pn} - C_{pi}\right)\right| \tag{2}$$

Where V is wind velocity at datum level (m/s), C_{pn} is the pressure coefficient at opening n, and C_{pi} is the pressure coefficient inside the room.

These above-mentioned cases were then simulated in Fluent program to estimate the facet pressure coefficients and airflow rate. The standard k-e model was used, where the same CFD settings explained above were implemented. Two wind directions were examined in each building configuration: 0° and 45°. In the 0° wind directions, the building was placed in a 30*30*20 m domain to simulate the ambient air. This means that domain dimensions were about six times the room dimensions. By rotating the room inside this domain, it was possible to simulate oblique wind direction. However, this required a larger domain to consider the increased sheer stress of the wind and ensure solution convergence. The previous size was gradually increased until a size of 50*50*20 m was achieved. This means that domain dimensions were about ten times the room dimensions. Results have been compared to the Network mathematical model, where a good agreement was observed (Table 3). A discrepancy that ranges between 2.2 and 7.8% in mass flow rate was observed. Furthermore, the study found that some inaccuracy is observed in the oblique wind case. This is related to the skew observed in the hexagonal mesh. The problem was avoided by using the tetrahedral meshing scheme.

TABLE 3. A summary of the validation study results (Asfour, 2007).

Case Description	Wind Direction	Inflow rate (kg/s)		Discrepancy (%)
		CFD	Network Model	
Square room with two opposite openings	0°	3.19	2.94	7.8
	45°	2.98	2.90	2.7
Rectangular room with two opposite openings on the short façade	0°	3.30	3.26	1.2
	45°	1.84	1.88	–2.2
Rectangular room with two opposite openings on the long façade	0°	1.83	1.87	–2.2
	45°	2.26	2.14	5.3

DesignBuilder 4.5

DesignBuilder is a whole building environmental simulation program that is commonly used in research and professional practice. It has a user-friendly graphical user interface and is considered a reliable research tool as it employs EnergyPlus as an energy simulation engine. EnergyPlus is a validated whole building energy simulation tool that engineers, architects, and researchers use to model energy consumption in buildings. It is considered a developed tool based on the two energy simulation engines DOE-2 and BLAST (US Department of Energy, 2015). DesignBuilder was used in this study to find out the internal temperature required for thermal comfort assessment, in addition to the internal air velocity estimated using CFD. The workflow of DesignBuilder starts with the drawing of the three-dimensional cases (illustrated in Table 1). After that, these cases have been modelled considering hot-dry and hot-humid climatic conditions. Two locations in the Middle East were selected: Cairo, Egypt, to represent the hot dry conditions, and Manama, Bahrain, to represent the hot-humid conditions. Table 4 shows the implemented thermal properties of building materials. Additionally, the following inputs were implemented in all cases:

- Building use: general office space.
- Occupancy and metabolic rate: 0.1 person/m^2, and 120 W/person, respectively.
- Clothing: 1 *clo* and 0.5 *clo* for winter and summer, respectively.
- Sensible gains: 10 W/m^2.
- HVAC system: natural ventilation (no heating or cooling).

TABLE 4. Thermal properties of building components modelled in DesignBuilder.

Element	Description	U-value (W/m².K)	Thermal Lag (hrs.)
External Walls	Cavity wall using concrete blocks	1.4	7.4
Windows	Double glazed with aluminium frame	1.9	NA
Ceilings	Concrete slab covered with tiles	2.6	6.8
Roof	Insulated concrete slab	0.7	11

Tropical Summer Index (TSI)

The Tropical Summer Index (TSI) is a thermal comfort assessment tool that was developed considering hot-dry and warm-humid climatic conditions. TSI is based on a three-year field study carried out in India and has been validated and compared with several thermal comfort indices. TSI is defined as: "the air/globe temperature of still air at 50% RH, which produces the same overall thermal sensation as the environment under investigation" (Sharma and Ali, 1986). This index was found appropriate for this study, which focuses on natural ventilation as a passive cooling technique in hot climates. Equation 3 is used to estimate TSI value:

$$S = 0.067\ t_w + 0.162\ t_g - 0.449\ V^{1/2} - 1.917 \qquad (3)$$

Where, S is the index value (°C), t_w is the wet-bulb temperature (°C), t_g is the global temperature (°C), and V is air speed (m/s). The global temperature here accounts for the effect of air temperature and radiant heat. Based on this equation, TSI psychrometric chart was produced, as depicted in Figure 3. This chart is practical, and facilitates studying the effect of dry-bulb

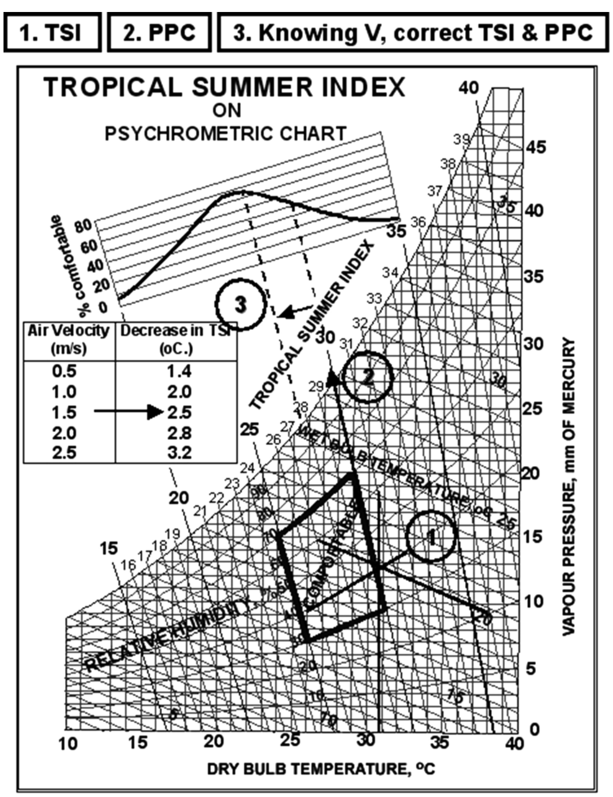


FIGURE 3. TSI psychrometric chart (Sharma and Ali, 1986), reproduced by the authors.

temperature (T_{db}), relative humidity (RH), and air velocity (V), on human thermal comfort. Value of T_{db} and RH are obtained from the thermal simulation process using DesignBuilder.

RESULTS AND DISCUSSION

In total, 18 cases have been modelled in the Fluent program. This resulted in a bulk of data that has been analysed and summarised below. This is done considering two dependant variables: the volumetric airflow rate to represent natural ventilation efficiency as a passive cooling technique, and the distribution of internal velocity magnitude to show the effect of natural ventilation on human thermal comfort.

A. Airflow Rate and Internal Wind Velocity

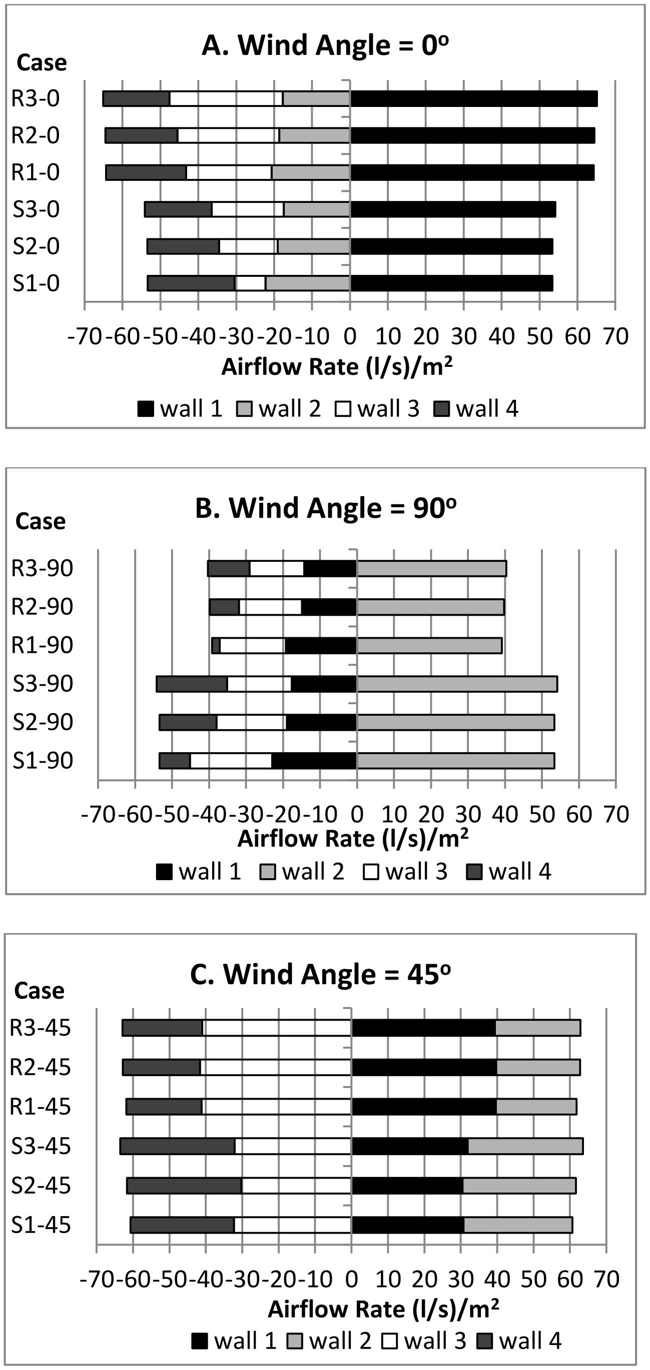
The first observed variable was airflow rate through the examined building openings. A general look at the graphs depicted in Figure 4 shows that these graphs are symmetrical. This is because the gross inflow rate and the gross outflow rate through building openings are equal. This is consistent with the law of mass conservation. Moreover, the effect of increasing plan area from S1 to S3, and from R1 to R3 on the resulting gross airflow rate in any wind direction is insignificant. This is because window area is proportional to plan area (10% of plan area).

It is possible also to notice that both building plan form and wind direction have a significant impact on the reported airflow rate. As for building plan form, Figure 4 shows that the highest airflow rate (65 $l/s/m^2$) is observed in the rectangular form when wind direction is 0°, i.e. when building's long façade faces the wind. This case has the shortest plan depth which equals 2.5H for R1, 3.3H for R2, and 4.1H for R3. By contrast, the lowest airflow rate (40 $l/s/m^2$) is observed in the rectangular building form when wind direction is 90°, i.e. when building's short façade faces the wind. Square cases performance in both 0° and 90° wind directions is the same due to building symmetry.

The case of oblique wind direction, modelled here at 45°, is possibly the most important one as it represents the normal relationship between wind currents and the building envelope. It can be noticed from Figure 4 that the performance of the square and rectangular building forms in this wind direction is almost the same. A volumetric air flow rate of about 60 $l/s/m^2$ was recorded. This is because building in this wind direction has two windward elevations, which increases wind deflection on the building and results in more airflow penetrating the plan.

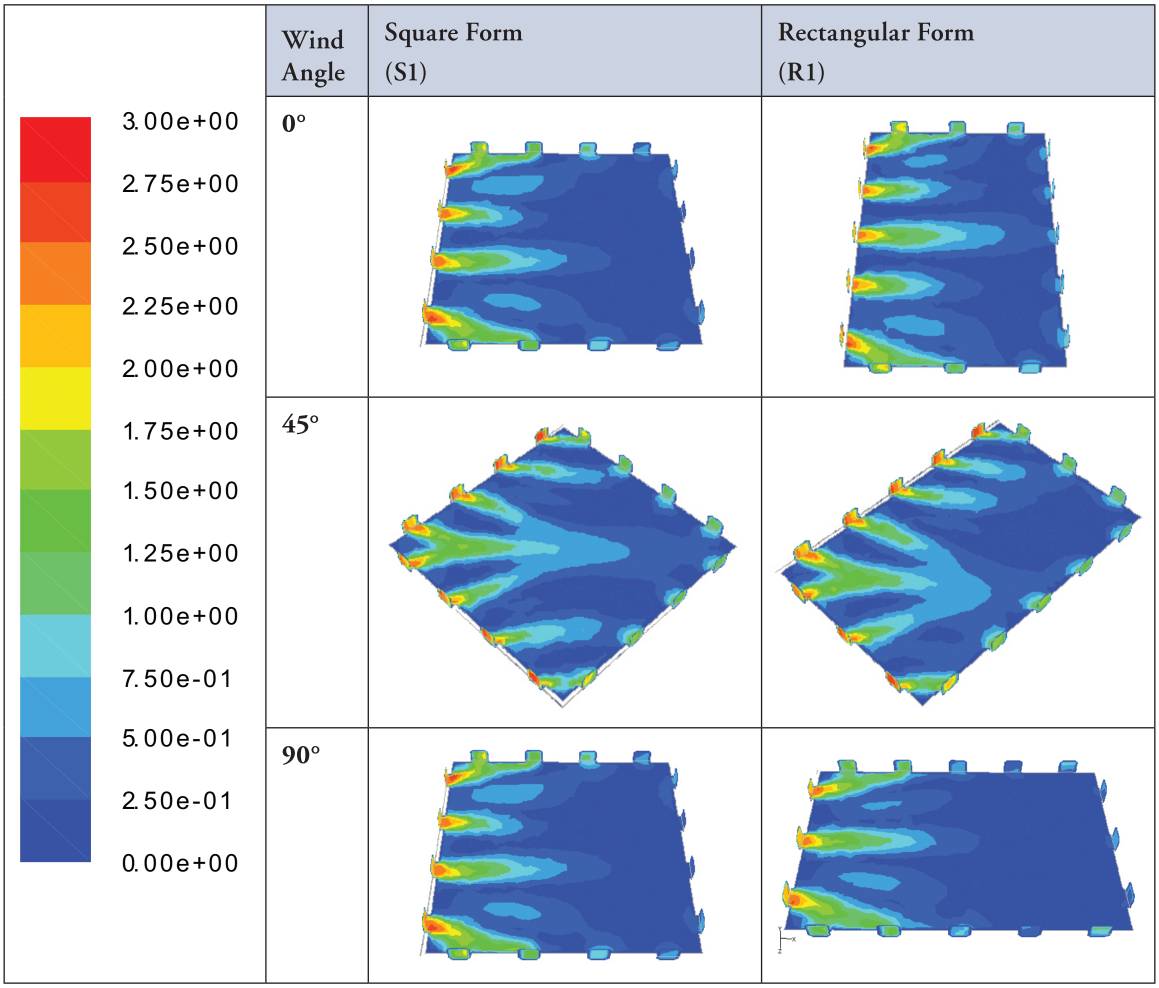
The second determinant of natural ventilation quality in buildings is the internal airflow distribution. Relying on the airflow rate is insufficient since lower airflow rates with normal distribution in the space are better than higher airflow rates that only serve a limited area of that space. Figure 5 shows a comparison of the internal airflow distribution presented by internal air velocity magnitude in the square and rectangular building forms. Cases S1 and R1 are only presented here in the three examined wind directions due to the similarity of wind behaviour between S1, S2, and S3 and between R1, R2, and R3. Results here correlate very well with the observations mentioned above in the analysis of volumetric airflow rate. In the case of 0° wind direction, better distribution can be noticed in R1 compared to S1. The latter case suffers from a large wind shadow area adjacent to the building's leeward façade. This shows that airflow current was unable to penetrate the whole depth of the plan, which did not exceed three times building height, i.e. 15 m. The situation is much better in R1, where the wind shadow area is trapped in the deepest corners of the plan. The situation is reversed in the perpendicular wind

FIGURE 4. Airflow rate through building openings.



direction (90°), where S1 performs better than R1. However, a large wind shadow area that covers around half of the interior space is observed in both cases. The oblique wind direction (45°) shows better internal airflow distribution in both building forms. Wind current reached the middle of the plan at a reasonable velocity magnitude (0.75 m/s), and wind shadow area has significantly ceased.

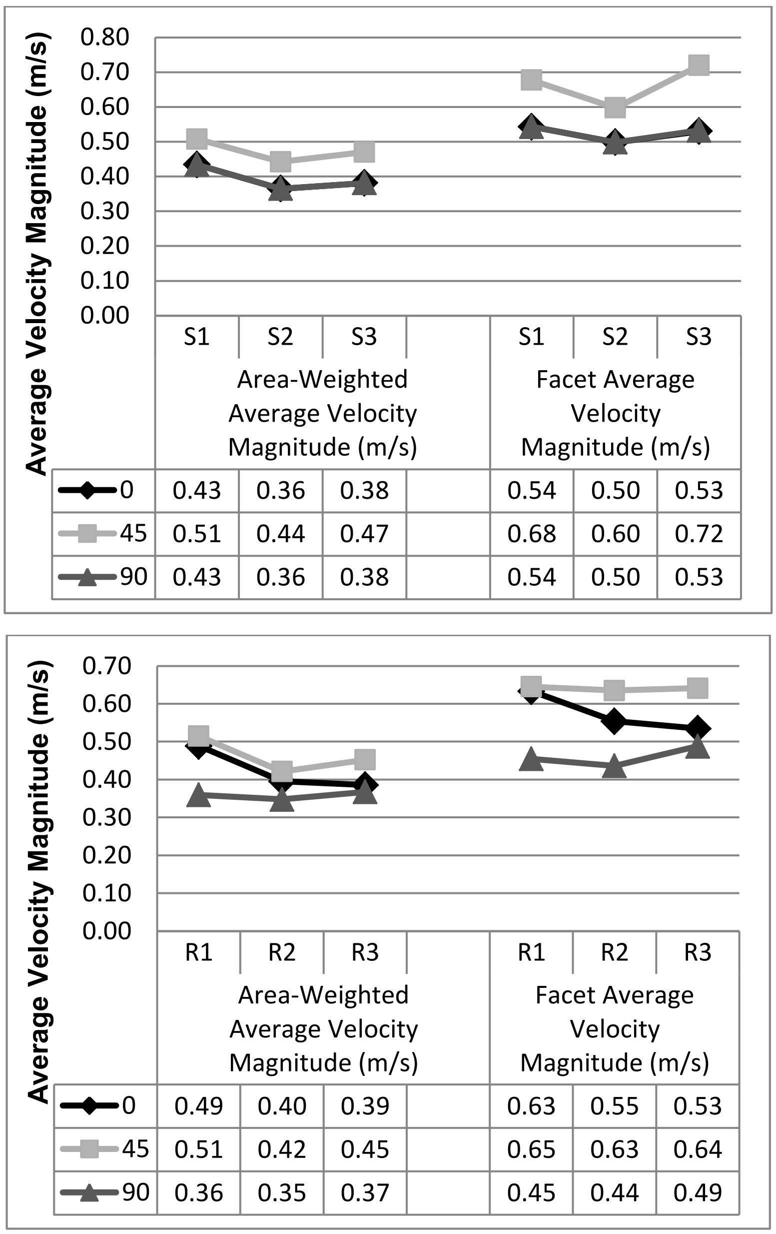
FIGURE 5. A comparison of internal airflow distribution presented by internal air velocity magnitude in the square (S1) and rectangular (R1) building forms.



To quantify the descriptive observations mentioned above, velocity magnitude was used to examine the internal airflow distribution for case S1 to S3, and R1 to R3, at the examined wind directions of 0°, 45°, and 90°. Two options exist here: to rely on the facet average value or the area-weighted value. Both options are measured across a horizontal plane that crosses the space at a height of 2 m. Figure 6 shows the results obtained using both options in the square cases (S1, S2, and S3) and the rectangular cases (R1, R2, and R3). It can be noticed that the facet average values are higher than the area-weighted values. However, the area-weighted average considers the frequency of occurrence of each internal velocity magnitude. This frequency is presented in the area of velocity contour of each magnitude as presented in Figure 6. Thus, the area-weighted option can be considered a more accurate option and will be used here as an indicator of the quality of internal airflow distribution.

In the case of 0° wind direction, it can be noticed that as plan area increased from S1-0 to S2-0, and from R1-0 to R2-0, the area-weighted average velocity magnitude ceased by 16% and 19% respectively. This occurs as a result of increasing building depth from 3H to 4H in the square cases, and from 2.5H to 3.3H in the rectangular cases. However, increasing plan area from S2-0 to S3-0, i.e. from 4H to 5H, and from R2-0 to R3-0, i.e. from 3.3H to 4.1H, resulted only in a slight reduction in the area-weighted velocity magnitude. This indicates that at some point of increasing the plan depth, cross ventilation becomes ineffective to penetrate the whole building depth and ventilation rate dramatically decreases. As indicated above, this occurred when plan depth exceeded 3H in the square cases and 2.5H in the rectangular cases. This point here is surely much less than the CIBSE recommended value of plan depth, which

FIGURE 6. Area-weighted versus facet average velocity magnitude (m/s) for the different cases (top: square cases, bottom: rectangular cases).



	Area-Weighted Average Velocity Magnitude (m/s)			Facet Average Velocity Magnitude (m/s)		
	S1	S2	S3	S1	S2	S3
0	0.43	0.36	0.38	0.54	0.50	0.53
45	0.51	0.44	0.47	0.68	0.60	0.72
90	0.43	0.36	0.38	0.54	0.50	0.53

	Area-Weighted Average Velocity Magnitude (m/s)			Facet Average Velocity Magnitude (m/s)		
	R1	R2	R3	R1	R2	R3
0	0.49	0.40	0.39	0.63	0.55	0.53
45	0.51	0.42	0.45	0.65	0.63	0.64
90	0.36	0.35	0.37	0.45	0.44	0.49

is 5H (CIBSE, 1997). This is in agreement with the findings of Chu and Chiang (2014), where ventilation rate drastically decreased only when the building aspect ratio L/H exceeded 1.25.

In the case of 90° wind direction, the situation is the same in the square cases due to building symmetry. As for the rectangular cases, no significant change was observed in the area-weighted velocity magnitude when increasing plan depth from R1-90 to R3-90, i.e. from 3.7H to 6.1H. Finally, the highest value of area-weighted velocity magnitude was observed in the case of the 45° wind direction. In case S1-45, this value is higher by 16% when compared to the 0° and 90° wind direction. In case R1-45, this value is higher by 4% when compared to the 0°, and by 29% when compared to the 90° wind direction. The observed behaviour of the relationship between increasing plan depth and the resulting average velocity magnitude is similar to the one observed in the 0° wind direction. As the plan area increased from S1-45 to S2-45, and from R1-45 to R2-45, the area-weighted average velocity magnitude decreased by 13% and 18% respectively. However, increasing plan area from S2-45 to S3-45 and from R2-45 to R3-45 resulted only in a slight reduction in the area-weighted velocity magnitude.

B. Thermal Performance Modelling

In total, 12 cases have been modelled in DesignBuilder program. As mentioned in the methodology section, DesignBuilder software has been used to find out the internal climatic conditions in the modelling cases, namely internal air temperature during the summer period. Thermal analysis was carried out for two square cases (S1 and S2) and two rectangular cases (R1 and R1) at the three considered wind directions in this study. Cases S3 and R3 have been excluded from the analysis since the observed average internal velocities at these two cases showed no significant difference compared to S2 and R2. Reference wind data are similar to those implemented in CFD. Average wind speed was chosen to be 3 m/s. Reference wind direction was varied between 0°, 45°, and 90° by rotating the building with respect to the prevailing wind direction. The study found that average internal air temperature in summer in the examined locations ranges between 30°C and 35°C.

C. Thermal Comfort Assessment

As mentioned in the methodology section, thermal comfort assessment has been carried out using TSI. Wind velocity obtained from CFD simulation, and internal air temperature obtained from DesignBuilder, are used in the analysis. Two values of relative humidity are assumed here: 30% and 70%. It can be noticed in the TSI psychrometric chart, depicted in Figure 3, that by knowing air temperature and relative humidity it is possible to find out the TSI value and the corresponding Percentage of People Comfortable (PPC), or on the opposite the Percentage of People Dissatisfied (PPD). Knowing internal air velocity (obtained from CFD simulation), TSI and PPC values can be corrected using the table attached to the chart depicted in Figure 3. In order to deal with the small values of indoor air velocity observed in this study, the table attached to the TSI chart has been interpolated as shown in Table 5.

Results obtained from this assessment are shown in Figure 7. This shows the effect of building plan shape and depth on thermal comfort performance under various wind directions, internal dry-bulb temperature, and relative humidity in summer. In general, the best improvement was recorded when the combination of the climatic inputs leads to a TSI value that falls between 28 and 34°C. At this zone, TSI psychrometric chart shows that a reduction of 1°C at

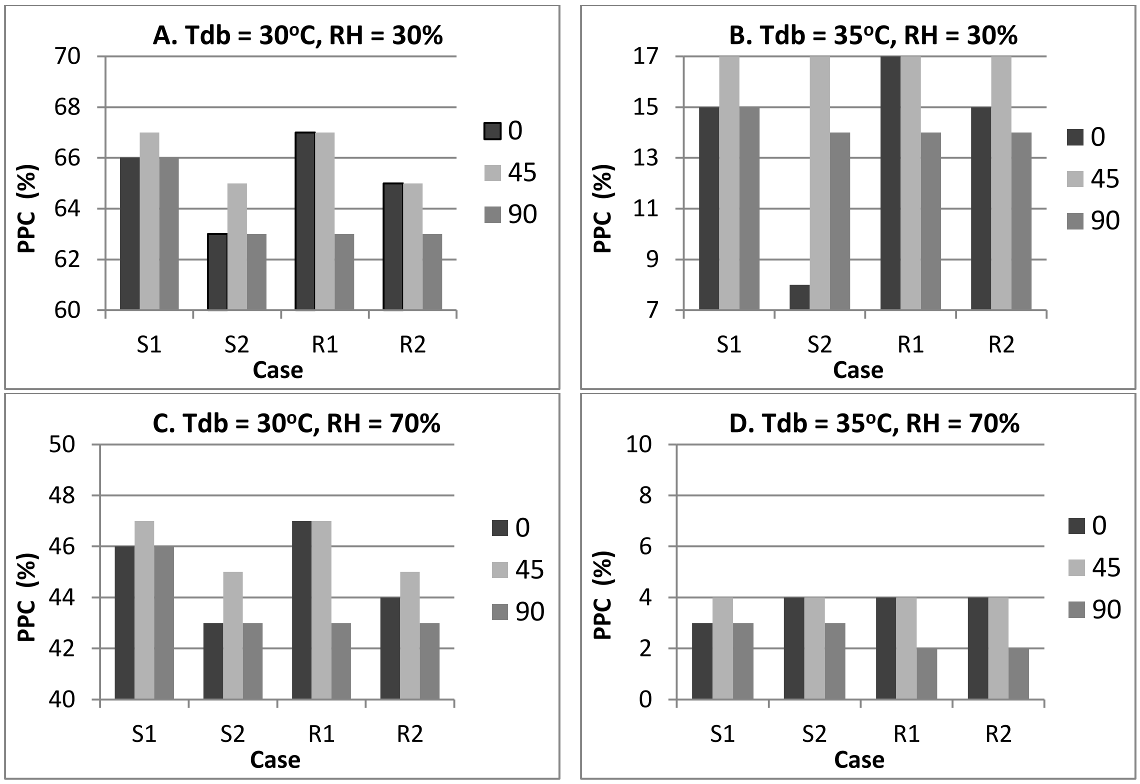
TABLE 5. The interpolated effect of internal air velocity on TSI value.

Air velocity (m/s)	Decrease in TSI (°C)
0.1	0.34
0.2	0.66
0.3	0.94
0.4	1.18
0.5	1.40
0.6	1.58
0.7	1.74
0.8	1.86
0.9	1.94
1.0	2.00

TSI value (due to increasing internal air velocity) leads to an increase in PPC by 10%. In general, a higher value of PPC was observed in the examined air temperature value of 30°C, but not in the value of 35°C. This is true for the both examined values of relative humidity, i.e. 30% and 70%. In category A (T_{db} = 30°C, RH = 30%) for instance, TSI value initially occurred within the highlighted comfort zone in the TSI psychrometric chart (Figure 3). Thus, the observed PPC value was relatively high in all cases (63–67%). On the opposite, category D (T_{db} = 35°C, RH = 70%), is based on climatic conditions that are outside the highlighted comfort zone in TSI psychrometric chart. Thus, the observed PPC value was relatively low in all cases (2–4%).

It can be noticed in general that increasing magnitude of area-weighted internal velocity has a positive effect on thermal comfort. The required increase in internal air velocity is achievable when wind direction is varied or plan depth is reduced. As for the wind direction factor, the best thermal comfort performance was observed in the 45° wind direction, since the average PPC in all the examined cases was about 33%. As for the plan depth factor, reducing building depth in the square cases from S2 to S1 had more potential to improve thermal comfort when compared to reducing the plan depth in the rectangular ones, i.e. from R2 to R1. The gross increase in PPC in all the examined wind directions and climatic conditions was 23% in the square cases, compared to 11% in the rectangular ones. In all cases, increasing internal air velocity should not lead to cause discomfort due to the undesired draught. For example, at internal air velocity of 1.5 m/s, hair and papers start to move, which may cause some discomfort for occupants in office buildings (Baker and Steemers, 2003). Instead, internal air velocity up to 2 m/s can be acceptable in other cases of overheated conditions (Szkolay, 2004).

FIGURE 7. The effect of building plan shape and depth on Percentage of People Comfortable (PPC) under various wind directions.



CONCLUSION

This study assessed the effect of building plan form on thermal comfort in naturally ventilated open-plan enclosures located in hot climates. The square and rectangular building forms have been considered in this regard in addition to a variety of climatic conditions and wind directions. The study utilised CFD to predict ventilation performance, DesignBuilder (EnrgyPlus) to calculate thermal parameters, and Tropical Summer Index (TSI) to assess thermal comfort conditions. These three tools were integrated in a quantitative approach to fulfil the abovementioned aim. It has been found that two factors should be considered in the assessment of wind-driven ventilation performance. The first one is the internal air velocity magnitude, while the second one is the internal air velocity distribution. The area-weighted average velocity magnitude estimated at the building occupants' level is more accurate when compared to the commonly used facet average value.

The study confirmed the common observation that the use of shallow building plans is an effective strategy to increase the potential of natural ventilation as a passive cooling strategy. This is more effective in the case of open-plan enclosures due to the absence of internal partitions. In this respect, the rectangular building form performs better than the square building in the case of 0° wind direction. The opposite is true for the 90° wind direction. At the oblique wind direction, 45°, both square and rectangular cases showed similar performance. However, the study found that some recommended 'rules of thumb' regarding the maximum possible plan depth in the case of using cross ventilation have to be re-examined. In general, increasing plan depth at any case reduces its internal air velocity magnitude. However, at some point of increasing the plan depth, the ventilation rate is dramatically decreased. In the three examined wind directions, this occurs when the plan depth exceeded 3H in the square cases and 2.5H in the rectangular ones, where H is the building height. This value is much less than the commonly recommended maximum value of plan depth, i.e. 5H, which should also be related to the plan form.

It has also been found that increasing the average internal air velocity does not guarantee a better thermal comfort in all cases. This is more challenging when both air relative humidity and temperature are high (70% and 35°C in this study). The required increase in internal air velocity is achievable when wind direction is varied or when plan depth is reduced. As for the wind direction factor, the best thermal comfort performance was observed in the 45° wind direction, which resulted in a better distribution of internal airflow. As for the plan depth factor, reducing building depth in the square cases had more potential to improve thermal comfort conditions when compared to the rectangular cases. This is because the gross increase in PPC was 23% in the square cases, compared to 11% in the rectangular ones. In general, the observed improvement in thermal comfort conditions was limited in most cases. This indicates the need for optimising the proposed natural ventilation system to ensure a higher internal air velocity. This is achievable through the adjustment of window area and height, the use of opposite windows with more opening area at the leeward façade to maximise the internal air velocity (Moore, 1993), and the use of non-symmetrical window distribution to improve the distribution of internal airflow (Stavrakakis, 2008). These strategies are recommended for further investigation.

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