INVESTIGATION OF WIND FLOW PATTERNS IN DENSE URBAN ENVIRONMENT OF AN EQUATORIAL TROPICAL CITY: A CASE STUDY IN SINGAPORE

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ABSTRACT

Wind Velocity Contours (WVC) and Wind Pressure Coefficient (WPC) were investigated to establish the opportunities for incorporating natural ventilation in early design stages of tall buildings in the Tropics. *Cham-Phoenics* software was used to carry out computational fluid dynamic investigations in the central business district of Singapore. The results showed that the average wind speed is between 5 and 6 m/sec. It was also concluded, that between the height of 150 to 250 m in a dense urban environment, the WVC and WPC on the building's surface are sufficient to create a wind tunnel effect through the year to allow for cross and stack ventilation as well as vertical wind catchers.

INTRODUCTION

A humid and warm climate is a characteristic of the tropical regions. It is, therefore, a common practice to use air-conditioning systems to achieve indoor thermal comfort. The expectations of ideal indoor comfort conditions range from 22.5°C-25.5°C for ambient indoor air temperatures and relative humidity of up to 70% (BCA, 1996) (ASHRAE Standard 55 1992). However, due to the prevailing climatic conditions of the region, outdoor temperatures are on average 7°C to 10°C higher, with a relative humidity of up to 90% throughout the year (Meteoblue AG 2020). It has an immediate effect on the indoor conditions of buildings, leading to a need for mechanical ventilation for cooling and dehumidification all year round.

With the change in the lifestyle as well as the globalization of work practices, the energy consumption and associated costs for the operations of buildings are high. A significant proportion (up to 60%) of operational energy in tropical buildings is dedicated to maintaining indoor thermal comfort conditions in both commercial and residential buildings (Qi 2006). Although more energy-efficient Air Conditioning and Mechanical Ventilation (ACMV) systems are being made available, the process of mechanical cooling remains largely energy-intensive. Beyond the energy consumptions, related CO_2 emissions and associated costs, air-conditioning (AC) systems emit a considerable amount of heat into the building's immediate surrounding, thereby adding to the causes of Urban Heat Island (UHI) effects (Oswald 2016). The largest contributor of heat emissions (89%-96%) globally is heat emitted from the buildings as suggested in the global-scale urban consumption of energy model (Lindberg et al., 2011).

As has been highlighted by the author of the book *"Reduce A/C (...)"* (Oswald 2016), in the regions of the subtropical and tropical Asia, excessive deployment of AC systems has given rise to serious problems related to the Urban Heat Island (UHI) due to explusion of the waste heat. Yet, very few buildings actually address the issues. The book indicates the importance of application of natural ventilation to reduce the energy consumption to increase thermal comfort of the occupants in high-rise residential buildings of the region.

Natural ventilation is an essential passive strategy that has been traditionally implemented in a hot and humid climate. The modern-day use of natural ventilation has advantages beyond the reduction of energy consumption and greenhouse gas emissions. It has the potential to increase the quality of both indoor and outdoor thermal comfort conditions (Aflaki et al., 2015). The use of natural ventilation in office buildings has decisively proven to reduce the occurance of the sick building syndrome (Fisk 2002). A study by (Brager et al., 2009), suggests up to 18% savings in health-related costs of occupants in naturally ventilated buildings in comparison with buildings that are mechanically ventilated.

Finally, to address the focus of the building typology for the study, it is important to look at the energy consumption statistics of the building sector in the Tropics. The commercial building sector, as seen from the study conducted by (Qi 2006), consumes about 12% more total energy as compared to the residential sector in Singapore. It is because most of the commercial buildings that average at the height of 150-200m, in the dense urban setting of tropical megacities are designed as sealed glass boxes, which are subjected to high solar gains and fail to use outdoor conditions to their benefit as illustrated in Figure 1. Beyond the high solar impact on the glass facades, the UHI causes higher outdoor temperatures that in turn adds to the indoor comfort conditions considerably.

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Figure 1: Central Business Districts of four tropical cities: Singapore, Kuala Lumpur, Bangkok and Jakarta. Source: Internet Images

The three parameters responsible for effective implementation of natural ventilation within a building are ambient indoor air temperature, relative humidity and air velocity (Szokolay 2012). Passive design strategies for building envelopes have the capability to modulate the indoor air temperatures and the air velocities. Building heights have a significant role in influencing the air velocities. It is suggested by *(Hindrichs et al., 2007),* that the heights above water bodies or flat grounds have a proportionate effect (increases) on the wind velocities. However, over an urban environment, the speeds decrease as the boundary layers begin at higher heights *(Hindrichs et al., 2007).* Hu, X-M defines boundary layers as "*the lowest part of the troposhere that is directly influenced by the presence of the earth's surface, and responds to surfae forcing within a timescale of about an hour or less*" (Hu, 2015).

When designing buildings for wind-driven ventilation opportunities, the most apparent investigations must be first concerned with wind scenarios at the local neighbourhood level (macro-scale). Subsequently, the wind flow patterns around the building must be understood, where the building's immediate surroundings (meso-scale) may act as obstacles to hinder the effective intake or use of the available wind velocity and pressure. Finally, conditions must be analyzed at the building level, where its orientation, shape, aspect ratio, façade designs, aperture sizes, numbers and height would affect the ventilation strategies (micro-level) (Oswald 2016). The study is an example to conduct a preliminary investigation at the macro and meso-level.

To undertake any building design for natural ventilation purpose, a preliminary investigation to quantify the possible wind scenarios in a specific setting is essential. Two important factors for wind scenario assessments are the measurements associated with wind speeds that surround the building and pressure excreted on the building facade. The parameters of these measurements are calculated as wind velocity contours (WVC) and the wind pressure coefficients (WPC) respectively. WVC and WPC are vital parameters when designing high-rise buildings for wind-driven ventilation systems. WVC are the contour lines that illustrate the speed and the direction of the wind around the building while taking into account the building geometry and the obstacles that may alter the wind flow and speed around the buildings. WPC is a dimensionless value which denotes the wind-induced pressure at a specific point in a building, relative to the freestream wind pressure (Charisi et al., 2019).

Therefore, this paper aims to investigate the wind scenario parameters of WVC and WPC for effective application of natural ventilation strategies for high-rise commercial buildings set in a dense urban environment in an equatorial tropical city of Singapore.

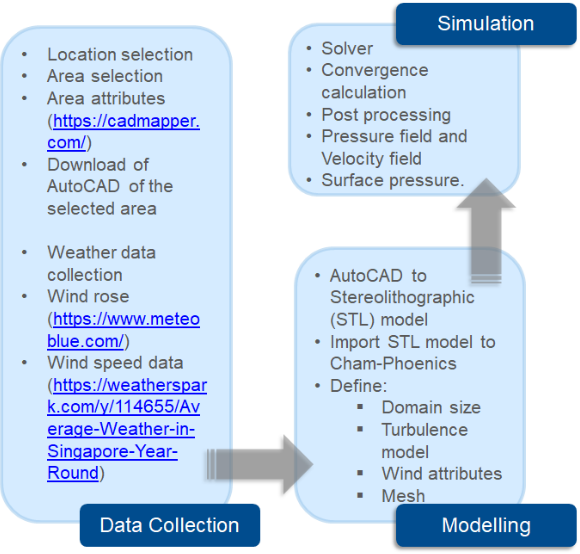
METHODOLOGY

The study focuses on quantifying the WVC and the WPC on an example set of buildings in the central buisness district (CBD) of Singapore. To do the same, Computer Fluid Dynamic (CFD) simulation technique was employed. The details of the modelling and simulations are stated in the following sections.

In order to ensure effective wind-driven cross ventilation a maximum differential between the windward and leeward values of WVC and WPC is ideal. However, the intake of the air for ventilation purposes can then be regulated through building façade design to eliminate drafts for thermal comfort conditions, yet ensuring that the desired air-speed is achieved for effective air exchange (circulation) within a space.

Modelling

The details of the methodology are presented in Figure 2.



- Location selection
- Area selection
- Area attributes (https://cadmapper.com/)
- Download of AutoCAD of the selected area
- Weather data collection
- Wind rose (https://www.meteoblue.com/)
- Wind speed data (https://weatherspark.com/y/114655/Average-Weather-in-Singapore-Year-Round)

- AutoCAD to Stereolithographic (STL) model
- Import STL model to Cham-Phoenics
- Define:
  - Domain size
  - Turbulence model
  - Wind attributes
  - Mesh

- Solver
- Convergence calculation
- Post processing
- Pressure field and Velocity field
- Surface pressure.

Figure 2: Methodology for Data collection, Modeling and Simulation

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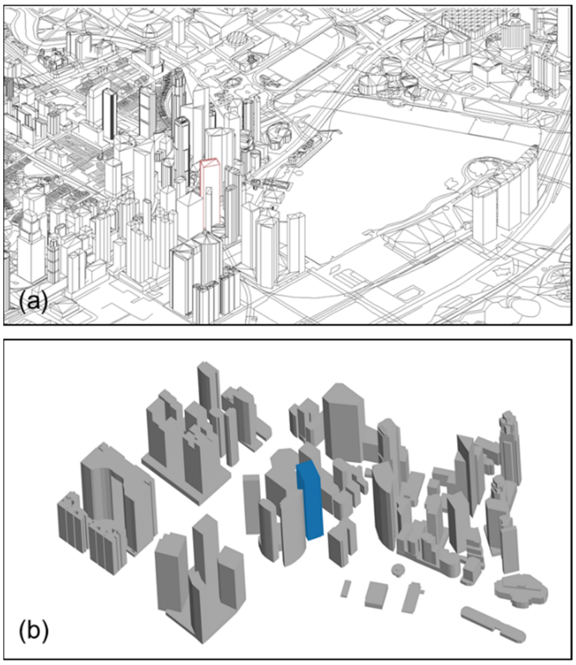

Figure 3: (a) AutoCAD Model (b) STL Model

Simulation

Simulations were carried out for North-North West (NNW) and South-South East (SSE) wind scenarios, as these are the two prevailing wind directions for Singapore as seen from the wind rose diagram in Figure 5. For the simplicity of simulation, a constant wind velocity of 4.7 m/s and 2.3 m/s was used for all levels in two wind scenarios.

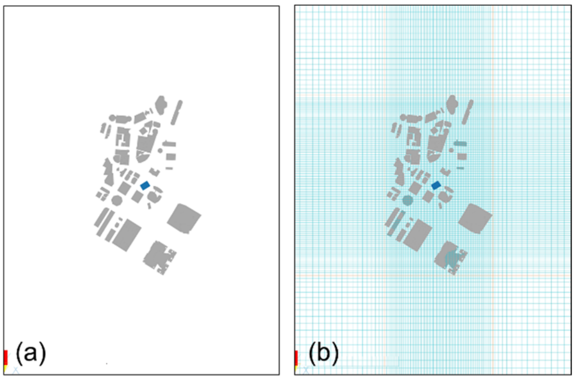

Figure 4: (a) Computational Model (b) Meshing Model

Table 1:Boundary Conditions for CFD Simulation

PARAMETER	VALUES
Wind Direction and Speed	N, 4.7m/s &S, 2.3m/s
Power Law Index	0.28
Area Size (m)	702 x 1168 x 283
Domain Size (m)	1800 x 2400 x 420
Turbulence Models	kε model
Reference Pressure (Pa)	101325
Ambient Pressure	0
Number of Iterations	5000
Density (constant) (kg/m^3)	1.189
Viscosity (constant)	1.54E-05

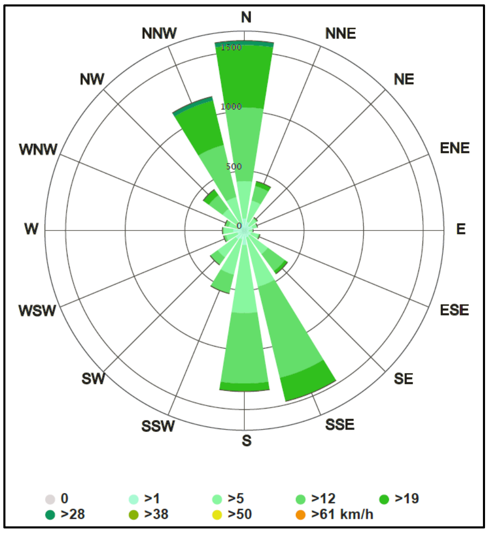

Figure 5: Wind Rose diagram for Singapore (Meteoblue AG 2020)

For WVC, simulations were carried out from 150 m to 250 m at an interval of 25 m. To establish the WPC on each face of the building, dynamic-wind pressure was computed at 75, 175 and 225m from the ground level. The values for WPC were calculated using Equation (1).

$$C_p = \frac{(p - p_\infty)}{(0.5 * \rho * U_\infty{}^2)} \qquad (1)$$

Where, C_p is the WPC, p is the pressure at the point of interest, $p_\infty$is the pressure in the freestream,ρ is the freestream air density, and U_∞ is the freestream wind velocity at the building height (Costola et al., 2009) (Charisi et al., 2019).

Table 2 details the values of $\boldsymbol{p - p_\infty}$ used for calculations at different levels for the North Wind Scenario (NWS) and South Wind Scenario (SWS). These values were obtained from the simulations.

Table 2: $\boldsymbol{p\text{-}p_\infty}$ values used for calculating WPC

FACADE	HEIGHT	$\boldsymbol{p - p_\infty}$ (NWS)	$\boldsymbol{p - p_\infty}$ (SWS)
South	75 m	-2.5	4.5
	175 m	-4.9	3.3
	225 m	-4.2	1.8
North	75 m	3.3	-2.1
	175 m	3.7	-3.3
	225 m	2.4	-4.4
West	75 m	-1.6	-2.9
	175 m	-3.4	-0.8
	225 m	-2.2	-0.8
East	75 m	6.9	-1.8
	175 m	11.3	-2.4
	225 m	4.7	-2.9

Table 3 details the values used for ρ and U_∞ in NWS and SWS.

Table 3: Values of $\boldsymbol{\rho}$ and $\boldsymbol{U\infty}$ used to calculate WPC

ρ (kg/m^3)	$\boldsymbol{U_\infty}$NWS (m/s)	$\boldsymbol{U_\infty}$SWS (m/s)
1.1521	4.7	2.3

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RESULTS

Results for three topics are presented. Firstly, WVC and pressures at the domain and secondly, at building level. Finally, the third section describes results computed for WPC at building level. The domain level is the neighborhood level of the selected building (macro level). The domain size for the study is listed in Table 1. More details are discussed in the following sections.

Wind Velocity Contours at Domain Level

The results of simulations at the domain level consists of external surface pressures exerted on the building faces. Figure 6 shows, that the positive pressure on the windward side ranges between 1 and 5 Pa in each of the two wind simulated wind scenarios. Similarly, the negative pressure on the leeward side range between -5 and 0 Pa.

Figure 7 illustrates the results for the pressure distribution and the WVC for the NWS, at the selected site area throughout the domain from the height of 150 m from the ground level to 250 m. It was noted, that for the NWS within the domain the maximum pressure and wind velocity on the windward side is 10 Pa and 8bm/s respectively. On the leeward side, the pressure and wind velocity values are -7 Pa and 3 m/s, respectively. On average, the domain experiences an average pressure of 5 Pa on the windward side and -3.75 Pa on the leeward side. The average wind velocity within the domain on the windward side was observed at 5.5 m/s and 2.5 m/s on the leeward side.

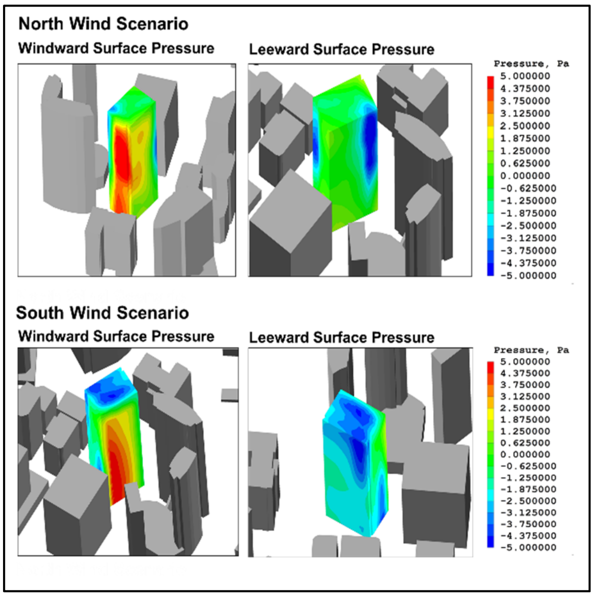

Figure 6: Domain Result- External surface pressure on building faces

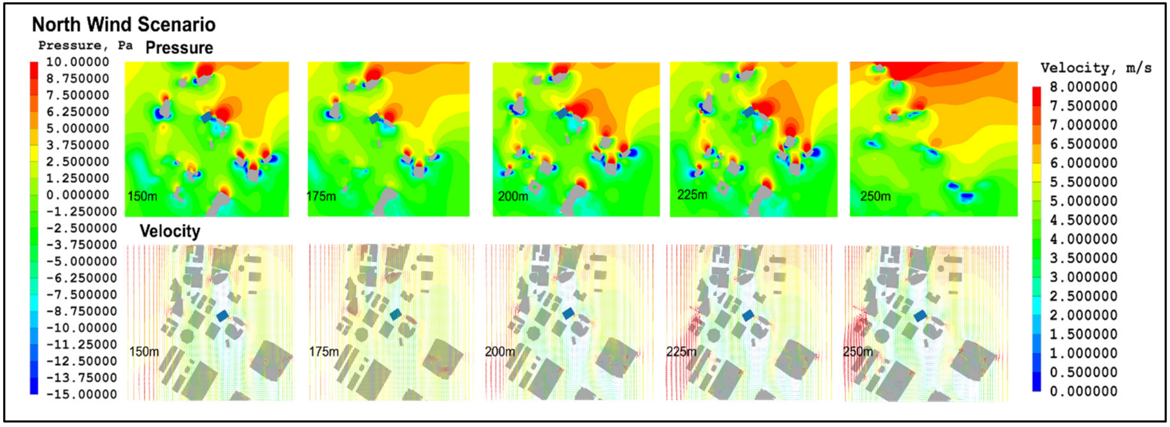

Figure 7: Domain Result- North Wind Scenario simulation result for pressure and WVC from 150 – 250 m

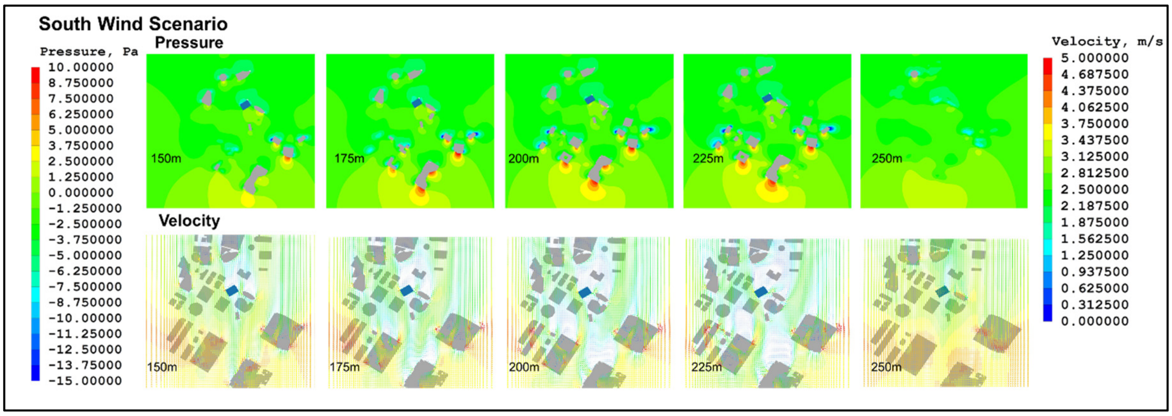

Figure 8: Domain Result- South Wind Scenario simulation result for pressure and WVC from 150 – 250 m

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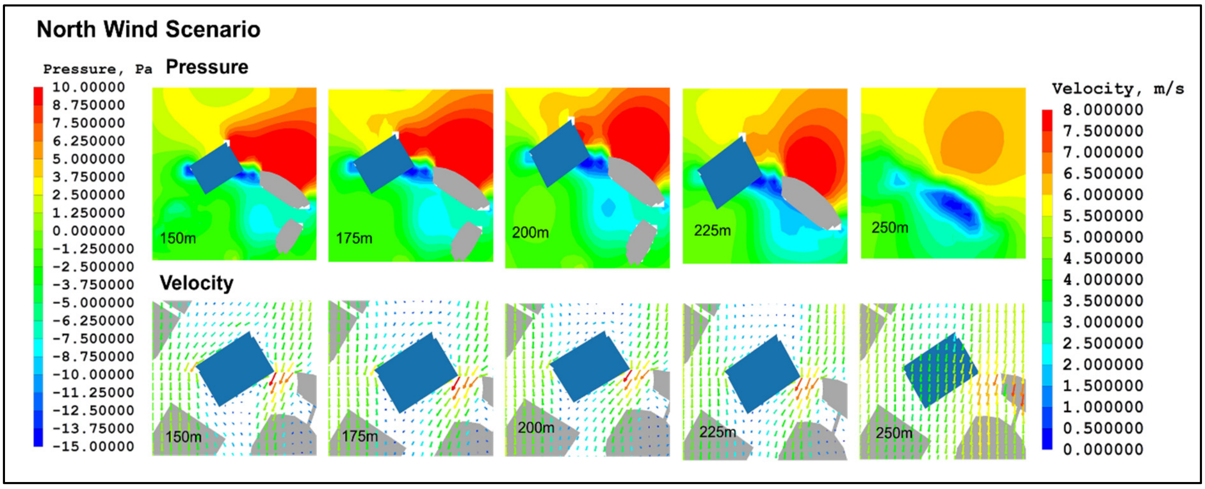

Figure 9: Building Result- North Wind Scenario simulation result for pressure and WPC from 150 – 250 m

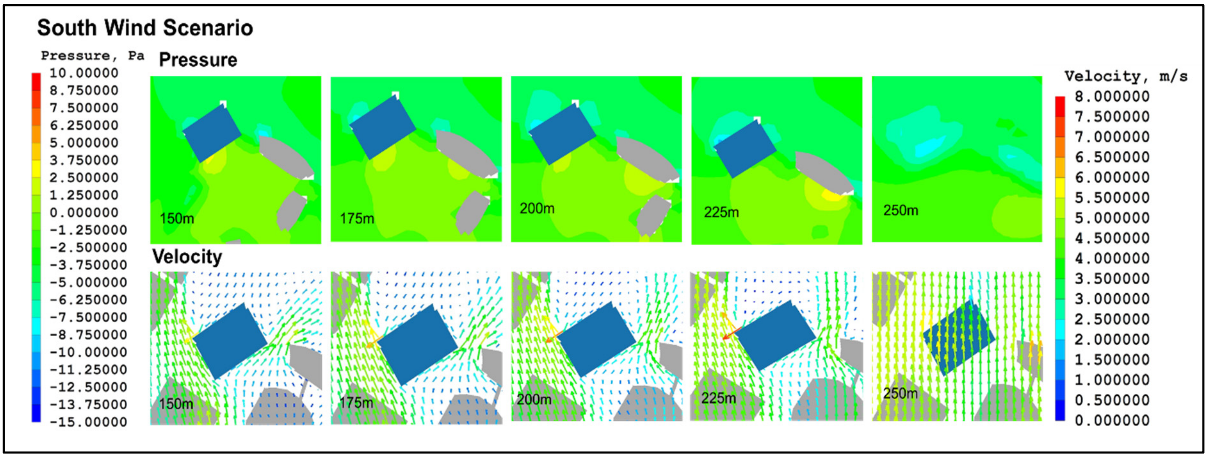

Figure 10: Building Result- South Wind Scenario simulation result for pressure and WPC from 150 – 250 m

Figure 8 shows similar results for the pressure distribution and the WVC for the SWS. It was noted, that for the SWS within the domain, the maximum pressure and wind velocity on the windward side is 3.75 Pa and 5 m/s respectively. On the leeward side, the pressure and wind velocity values are -3.75 Pa and 1.87m/s, respectively. On average, the domain experiences an average pressure of 2.5 Pa on the windward side and -2.5 Pa on the leeward side. The average wind velocity within the domain on the windward side is observed at 3.45 m/s and 2.10 m/s on the leeward side.

Wind Velocity Contours at Building Level

Figure 9 shows the results of the NWS simulation at the building level. The results are for 150 to 250 m above the ground. It was concluded from the result that the range of surface pressure on the windward side of the building ranged between 2.5 to 6 Pa at various heights. Similarly, the results for the leeward side suggest the range of negative surface pressure varies between -5 to -1 Pa. In terms of wind velocity around the building, the range was observed between 4.5 to 6 m/s on the windward side. Whereas, on the leeward side, the range of wind velocity was noted between 1.5 to 2.5 m/s.

Figure 10 shows the results of the SWS simulation at the building level. The results are for the same heights as specified in NWS. The range of surface pressure in SWS, on the windward side of the building, lies between 1.25 to 2.5 Pa at various heights. Similarly, the results for the leeward side suggest the range of negative surface pressure ranges between -6.25 to -3 Pa. In terms of wind velocity around the building, the range was observed between 2 to 3 m/s on the windward side. Whereas, on the leeward side, the range of wind velocity was noted between 0.5 to 1.5 m/s. Overall, in the SWS wind velocities are significantly lower on the windward and leeward side than in the NWS. This is due to the low wind speeds from the SSE direction as seen in Figure 5.

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Wind Pressure Coefficients at Building Level

The simulation at building level also provided values for $\boldsymbol{p} - \boldsymbol{p}_{\infty}$ stated in column 3 and 4 of Table 2. These were then used to calculate the values of WPC (denoted as Cp) indicated in column 3 and 4 of Table 4 using Equation 1. Figure 11 and 12 show the WPC of various facades at 75, 175 and 225 m from the ground for the two simulated wind scenarios. The tabulations of the values of the coefficients are stated in Table 4. As seen in Figure 11, in the NWS, the WPC is positive on the windward side (North and East Façade) while it stays negative on the leeward side (South and West Façade).

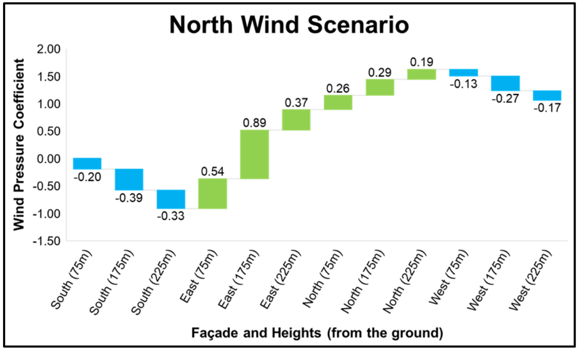

Figure 11: WPC (Cp) for NWS

However, for the SWS, the values of the WPC remain negative on three sides of the building (East, North and West) as seen in Figure 12.

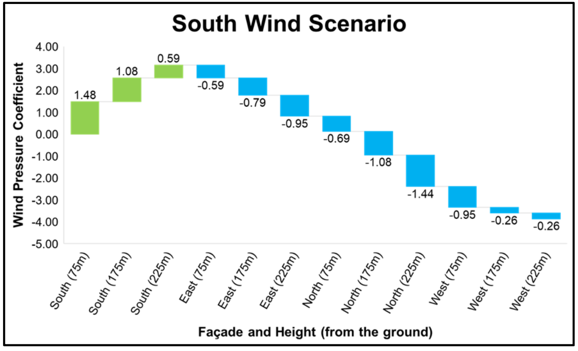

Figure 12:WPC (Cp) for SWS

Table 4: C_p at various heights on different facades

FACADE	HEIGHT	C_p (NWS)	C_p (SWS)
South	75 m	-0.196	1.477
	175 m	-0.385	1.083
	225 m	-0.330	0.591
North	75 m	0.259	-0.689
	175 m	0.291	-1.083
	225 m	0.189	-1.444
West	75 m	-0.126	-0.952
	175 m	-0.267	-0.263
	225 m	-0.173	-0.263
East	75 m	0.542	-0.591
	175 m	0.888	-0.788
	225 m	0.369	-0.952

Although the simulations are carried out from level 150 to 250 m at an interval of 25 m, there is no major change in the WVC. It may be due to the fact that

DISCUSSION

One of the ways to understand the wind scenarios prevailing within the immediate surrounding of a building is by employing CFD simulation techniques. The results of CFD simulation lends a vivid insight on not only the WVC available at various heights along the Z-axis, but also allow a clear understanding of the wind flow pattern along the building and its immediate surroundings as seen in Figures 7-10. Beyond the visual results, the simulation also provides numerical values important for computing various other parameters, for example, for the present study, the calculation of WPC values.

Comparison of the Wind Scenario- Domain Level

As suggested in Figure 5, the predominant annual wind directions in Singapore are NNW and SSE. From the simulated wind scenario cases, it was inferred that to maximize the potential of natural ventilation, the intake façade of a building should be oriented in the North-South direction. The wind velocity and pressure differential in the NSW have the potential to effectively carry out wind-driven cross ventilation in buildings with narrow floor plates. The WVC and surface pressure for the SWS, on the other hand, are not as effective for wind-driven natural ventilation, but the orientation can be used for fresh air intake for hybrid ventilation systems.

Comparison of Wind Scenario-Building Level

As suggested in the previous section of the discussion, it was inferred that the NWS works the best for the case study under investigation at the domain level. From the results, it can also be inferred that the same is true at the building level.

Two other observations were noticed at the building level investigation. The pressure and wind velocity at the corner of the buildings on the leeward side were much higher than on the windward side. This is caused by the airflow being incapable of negotiating sharp corners (Gupta et al., 1993), resulting in the separation of flow from the boundary surface (Davenport 1960).

The phenomenon is more prevalent in the NWS.
Secondly, it was also observed, as seen in Figure 9, that a wind tunnel effect is created between two adjacent buildings with similar heights. The distance between the two buildings (20 m) and their similar heights (245 m) created a significant pressure differential causing the wind to pass through the two buildings with higher velocities of 8 m/s as compared to the 5.5 – 6 m/s on the free side. While orienting a building in a wind shadow area of two closely spaced buildings in a dense urban environment, the phenomenon can be used to an advantage.

Although the simulations are carried out from level 150 to 250 m at an interval of 25 m, there is no major change in the WVC. It may be due to the fact that

above the built environment wind velocity decreases as the boundary layer begins at a greater height (Oswald 2016).

Comparison of Wind Pressure Coefficients-Building Level

When conducting investigations for wind-driven natural ventilation, WPC on different facades of the building play an important role. For the study of building physics and engineering, WPC is used to calculate wind loads of the building faces as well as for calculation of wind-induced infiltration (Charisi et al., 2019) (Liddament et al., 1996). Microclimates for building energy simulation can be introduced through WPC subsequently enabling a more accurate prediction of wind induced air-infiltration (NV) (Charisi et al., 2019), (Charisi et al., 2019) (Charisi et al., 2017). For high-rise buildings the WPC *(C_p)* values vary significantly along the height (Z-axis), hence it is appropriate to use localized *Cp* values Charisi et al., 2019).

Like for the wind scenarios at the domain and building level, the NWS was proven to have a better performance with the computed *Cp* values than the SWS. From the values of the NWS, it could be inferred that the windward façade had positive *Cp* values, and the leeward side had negative *Cp* values which evidently support unhindered cross ventilation through a built structure. However, the values of the SWS suggest negative *Cp* values on three sides of the building, which is not suitable for wind-driven natural ventilation unless the openable apertures are only placed on the North and South façade.

Beyond the application of the current methodology as discussed above, a simulation based study provides valuable data (WPC and WVC) which can be used for advance design stages. In a simulation study, real life situations are modeled up to a near accuracy to produce results that provide an accurate overview of the space performance that is being investigated. When the modeling and input data is accurate the simulation results can be trusted by designers to make informed decisions. Furthermore, computer based simulation studies save designers and developers a lot of capital investment for carrying out long and tedious processes such as wind tunnel testing. It is therefore highly recommendable to carry out simulation based CFD investigations at the early design stages of a building to ensure enough NV opportunities can result into a high performance, modern day building.

CONCLUSION

It is a fact that natural ventilation has physical and physiological advantage for the building and its occupants. The physical (energy related) advantages are now easily quantifiable. However, when it comes to the quantifying the physiological benefits there still remains an ambiguity regarding the results of such studies. This is because physiological benefits are measured using thermal comfort models. Thermal comfort models quantify the combination of indoor space environment and personal factors which produce thermal environmental conditions which are acceptable to 80% or more of the occupants within a space (ASHRAE, ANSI 1992). The current standard for occupant thermal comfort is based on the heat balance model of the human body. This model predicts that the thermal sensation is exclusively influenced by environmental factors such as temperature, thermal radiation, humidity and air-speed and occupant personal factor such as activity and clothing (Brager et al., 2001).

A recent study (Aynsley 2007) suggested, that, in warm climatic conditions, the elevated air speeds from either natural ventilation or a mechanical fan have the potential to offer a temperature offset of 9°C. Based on this principle, it can be infered that in a humid climate like that of Singapore, the presence of elevated air velocity aides in evaporative and convective cooling from human skin. (Kwong et al., 2014). When buildings make use of natural ventilation for elevated wind-speed purposes, the process can benefitial for energy efficiency as well as occupant comfort. For all the reasons stated above, it is highly recommended that more high-rise, commercial buildings in the tropics (which are energy intensive in their daily operations) must incorporate natural ventilation strategies as a passive measure to decrease their operational energy consumption.

Although the study started as finding natural ventilation opportunities for hot and humid climatic conditions, it can be conclusively suggested that every site in question must be evaluated individually. The methodology used in the current study for primary investigation can be universally applied for all similar studies. From the current study, it can be concluded that between the height of 150 to 250 m in a dense urban environment like that of Singapore, the WVC as well as the pressure on the surface of the building is enough to create a wind tunnel effect through the year to allow for cross and stack ventilation. However, the wind velocities at these heights are too large to allow an uncontrolled intake (via operable windows). Therefore, the recommendation from this study would be to test out façade designs which can slow down the air velocity to a recommended speed of 0.25 m/s. In a study conducted in the hot and humid climate of Brazil, the range of acceptable air speed was between 0.5 and 1.5 m/s (Candido et al., 2008). It could also be applicable to a place like Singapore and other equatorial tropical regions.

Furthermore, understanding of WVC is not enough information to design natural ventilation strategies for any building, because WCP play a significant role in ensuring a smooth flow of wind-driven ventilation within a building. There is a significant correlation between the surface pressure and the adjacent buildings which affects the WVC and WPC. A proper preliminary investigation into both parameters can afford designers an opportunity to design relevant natural ventilation strategies for high-rise office buildings in a dense urban environment like that of a CBD in Singapore.

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