

Better Natural Ventilation Design for Single Sided Apartments Utilising Computational Fluid Dynamics

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Abstract: Wind-driven natural cross ventilation to many single-aspect apartments can be achieved via building indentations and façade articulation. The ventilation rate of these apartments will rely on pressures differences between openings caused by approaching wind pressure, local wind climate and interaction with the surrounding built environment and external pressure gradients on the building indentations or any other facades articulation and their potential driving force on natural ventilation. Detailed simulation methods are therefore required to consider all above mentioned parameters and provide internal and external airflow information to the design team to allow for design modifications or refinement where required to provide robust natural cross ventilation for such apartments.

This study assesses the above parameters for a proposed development, designed with recesses and slots to enhance natural cross ventilation in single-sided apartments, and presents a reliable procedure to advise on compliance with national and/or international design guidelines utilising an advanced combined outdoor-indoor Computational Fluid Flow (CFD) analysis integrated with localized weather data for the project site.

Keywords: CFD, Natural Cross Ventilation, Single Sided Apartments, Australian Design Guide, Multi-Residential Buildings.

1. INTRODUCTION

Buildings account for 30-40% of total energy consumption, and natural ventilation is an effective strategy to reduce energy consumption, especially in multi-storey residential buildings. Other advantages of natural ventilation include increased space usage (e.g. less ductwork), reduced maintenance, improved user satisfaction, etc.

Natural cross ventilation is achieved by apartments having multiple openings where there exists a pressure difference between those openings, e.g. if the wind pressure at one opening is greater than the pressure at other openings, airflow will be pushed through the apartment in the direction positive to negative.

Several factors should be considered when assessing the wind-driven natural ventilation potential of an apartment, including the following:

- Exposure to the prevailing local wind climate and exposure to higher strength winds on elevated terrain.
- Interaction with the surrounding built environment.
- External pressure gradient variations created by articulated facades and their potential driving force upon natural ventilation.

- Internal geometry, e.g. the presence of room partitioning will affect the pressure drop inside the apartment.

Consideration of the above factors will allow a reliable assessment of the impact of pressures differences caused by wind.

The prediction of wind-driven natural ventilation in single-sided apartments of high-density residential buildings has been the subject of a number of research and commercial studies. Examples are shown in [1-10]. Among the existing methods to predict the wind driven ventilation rate, there is:

- Empirical Method [6,7] for a single fronted unit with one opening. This model calculates the ventilation rate as:

$$Q = C_v A U$$

Where A is the opening area (half of the single opening), U is the reference wind speed and C_v is the value of the opening effectiveness. This approach can provide a rapid estimate, and the accuracy of the calculation will depend upon the approximated C_v values for various wind directions.

- Wind Tunnel Testing [8,9]. There are known limitations in the physical scale modeling of ventilation flow through the openings [8], which restrict the simulation of ventilation in wind tunnel models to cases where the external pressure

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distribution on a building is not impacted by the presence of openings and the resulting building airflow.

- CFD Modelling [9-11]. With advances in computational resources, a validation process for turbulence models and best practice of CFD guidelines, the use of CFD is rapidly increasing for natural ventilation and thermal comfort studies.

This study provides a reliable methodology and procedure to design effective natural ventilation for single sided apartments utilising CFD modelling of a combined external and internal built environment, including a detailed geometry of the proposed development, building indentation, façade articulation, internal apartment layout and the influence of surrounding buildings.

The numerical method allows for providing comprehensive output (velocity distribution in three dimensions, pressure profile, turbulence level, air changes per hour, etc.) and reporting whether or not compliance is achieved with regulatory requirements.

2. APARTMENT DESIGN GUIDE (ADG) REQUIREMENT

The Department of Planning, NSW, Australia lodged a new Apartment Design Guide (ADG) in June 2015 [12]. The ADG provides general guidance about how development proposals can achieve certain design quality principles.

The ADG is relevant to the assessment of the natural ventilation through the residential components of a proposed development. Section 4B-3 of the ADG states that:

- At least 60% of the apartments are naturally cross ventilated in the first nine storeys of the building. Apartments at ten storeys or greater are deemed to be cross ventilated only if any enclosure of the balconies at these levels allows adequate natural ventilation and cannot be fully enclosed.

Natural cross ventilation is deemed to be achieved by apartments having more than one aspect with direct exposure to the prevailing winds or windows located in significantly different pressure regions, rather than relying on purely wind driven air. Apartment layout and building depth have a close relationship with the ability of an apartment to be naturally ventilated. Generally, as the building gets deeper, effective airflow reduces.

Natural cross ventilation to many single aspect apartments is achieved via building indentations or stack effect ventilation (or similar) or courtyards or building indentations which have a width to depth ratio of 2:1 or 3:1 [12] to ensure effective air circulation and avoid trapped smells.

There are no specific requirements (e.g. air changes per hour) in the ADG guideline.

AS1668.2-2002 [13]: Ventilation design for indoor air contaminant control (excluding requirements for the health aspects of tobacco smoke exposure) recommends 3 air changes per hour for habitable rooms to satisfy air quality requirements.

In the absence of specific criteria in the ADG guideline, this study considers the 3-air changes per hour appropriate for the natural cross ventilation study considering all wind directions and localised wind speeds.

In terms of air velocity within a room, magnitudes of between 0.2 m/s and 0.7 m/s are generally considered desirable for the provision of so-called comfort ventilation. Higher velocities are desired with higher apartment temperature (especially above 27°C). Buoyancy driven ventilation that results from a temperature difference between the interior and exterior is not included in the ADG guideline.

The main objectives of this study are to:

- Analyse the local weather data for the project.
- Utilise 3D CFD modelling tools to reliably demonstrate wind driven natural ventilation in single-sided apartments.
- Develop a reliable procedure to advise on compliance with national and/or international design guidelines.
- Provide design modifications to improve natural ventilation where required.

3. PROBLEM FORMULATION

The CFD model solves the continuity and momentum and energy equations. The equations for a steady state case can be written as follows:

$$\frac{\partial}{\partial x_i} (\rho u_i) = 0$$

$$\frac{\partial}{\partial x_j} (\rho u_i u_j) = - \left(\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \right) + \rho g_i + F_i$$

$$\frac{\partial}{\partial x_i} (\rho h) + \frac{\partial}{\partial x_i} (u_i \rho h) = \frac{\partial}{\partial x_i} (k_{effective} \frac{\partial T}{\partial x_i}) + S$$

Where ρ is the density of air, u is the air velocity, p is the static pressure, g and F are the gravitational body and external body forces, τ_{ij} is the stress tensor, h is the enthalpy, $k_{effective}$ is the effective thermal conductivity and S is the volumetric heat source.

This current study focuses on wind driven ventilation and the energy equation is not solved.

4. CASE STUDY

4.1 Project Description

The project site is located in a suburban area in Sydney and is surrounded by low-rise commercial and residential buildings to the north, an existing shopping centre and carpark to the east and sports field to the south.

The proposed development consists of two blocks with a total of 72 residential apartments from Ground Floor to Level 3. A typical floor plan is shown in Figure 1.

The CFD model was used to model all prevailing wind directions.

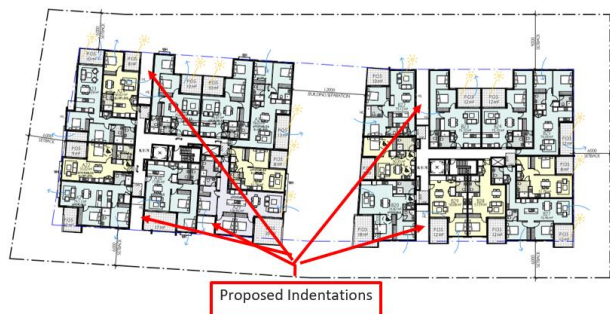


Figure 1: Typical Floor Plan for the Proposed Development.

4.2 Local Weather data

The data of interest in this study are the annual mean hourly wind speeds experienced throughout the year, how these winds vary with azimuth, and the seasonal break-up of winds into the primary Sydney wind seasons.

4.2.1 Local Meteorological Conditions

Local wind speed and direction influence naturally cross-ventilated units with areas of positive pressure on the windward side of a building and negative pressure on the leeward sides of the building. Wind direction and the variability in wind direction determine the extent of crosswind spreading. Surface roughness (characterised by features such as the topography of the land and the presence of buildings, structures and trees) affects the degree of mechanical turbulence, which also influences the rate of ventilation.

The Bureau of Meteorology (BoM) maintains and publishes data from weather stations across Australia. The closest such station recording wind speed and wind direction data is the Sydney Airport Automatic Weather Station (AWS), located approximately 11.7 kilometres (km) east of the Development Site (Station ID 66037).

This data has been analysed for the period 1999-2017. This dataset contains records at hourly intervals of:

- Mean Wind Speed - average wind speed during the 60-minute period
- Gust Wind Speed – peak 2-3 second gust occurring (any time) within the 60-minute period
- Wind Direction – average wind direction during the 60-minute period

The annual wind rose and seasonal wind roses for the years 1997-2017 compiled from data, recorded by the Sydney Airport AWS, are presented in Figure 2.

On an annual basis, the predominant wind directions in the area are consistently from the northeast, south and northwest directions. Very low frequencies of winds from the east were recorded across all years. The annual frequency of calm wind conditions was recorded to be less than 3%.

The frequency of occurrence statistics for various mean wind speed levels at the proposed building height is shown in Figure 3.

From the weather station data:

- There were 550 hours total (6.3% probability) where the mean wind speed is below 2 m/s, taking into account all wind directions.

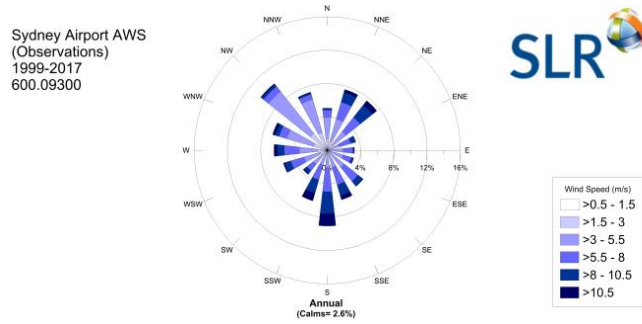


Figure 2: Sydney (Kingsford Smith) Airport Wind Roses: 1999-2017.

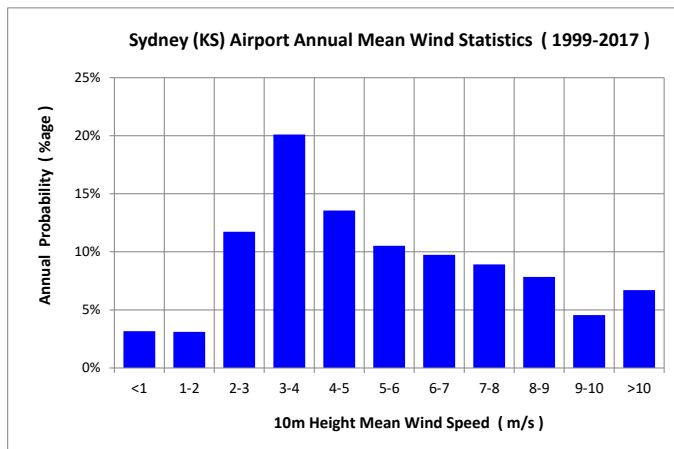


Figure 3: Mean Wind Speed Frequency of Occurrence for Sydney Airport: 1999-2017.

- Accordingly, the annual frequency of mean 10 m height wind speed exceeding 2 m/s recorded at Sydney Airport was very high, i.e., at 93.7%.
- The annual frequency of mean 10 m height wind speed exceeding 4 m/s recorded at Sydney Airport was also relatively high, i.e., at approximately 62%.

The wind conditions for the project site were predicted using CFD analysis for all prevailing wind directions. At the upwind free boundary, inlet velocity profiles were derived from Bureau of Meteorology data and the Australian Wind Code AS1170.2. At the downwind and upper free boundaries, constant pressure boundary conditions were applied.

4.3 Natural Cross Ventilation CFD Modelling

4.3.1 Modelling Configuration

A 3D model of the project site, surrounding buildings and structure blocks was created from the supplied

architectural drawings and a CAD Model supplied by the project architect. The developed model accounted for all small features of the proposed development (e.g. canopies, gaps, blades, etc.).

The geometry for CFD Modelling is shown in Figure 4 and Figure 5. A calculation domain of 2,000 m length, 2,000 m wide and 180 m high was used for the CFD analysis.

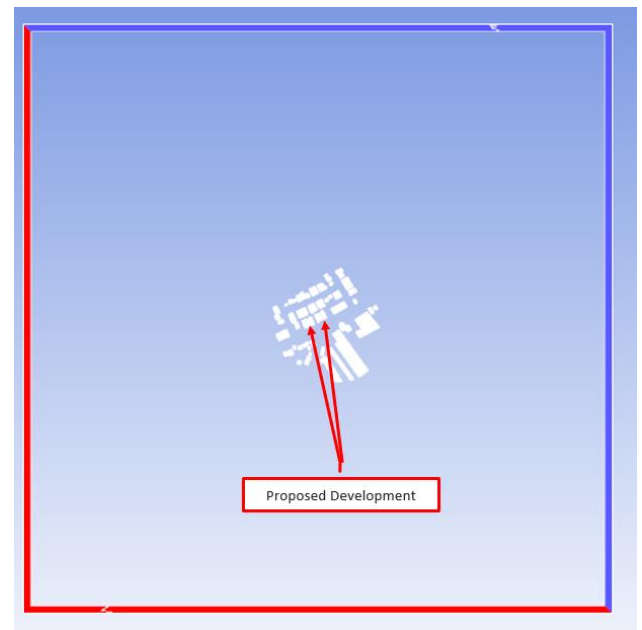


Figure 4: CFD Model of the Project Site and Surrounding Buildings.

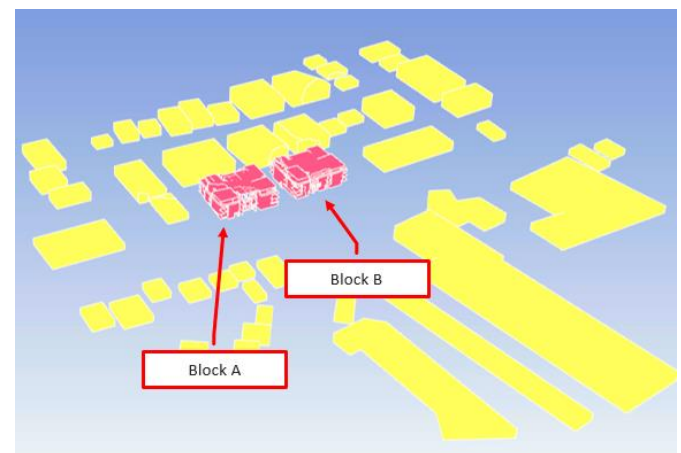


Figure 5: 3D Model for the project Site.

The CFD model accounts for detailed internal layout modelling, detailed site topography, building features and openings as per the provided architectural drawings. A two-dimensional section through a typical level is shown in Figure 6.

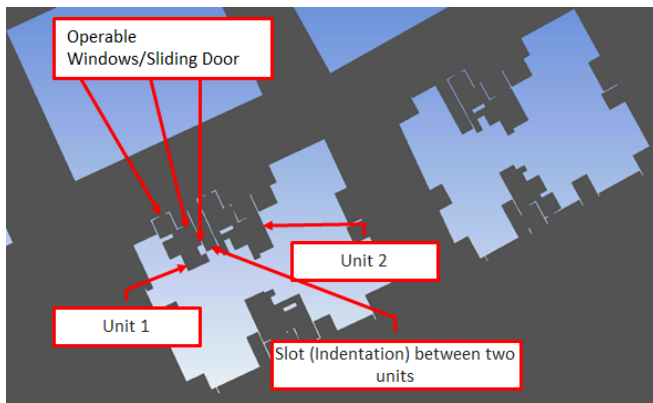


Figure 6: Areas of Interest – Typical Floor Plan.

4.3.2 Sensitivity Analysis

4.3.2.1 Extent of Built Environment

The size of the computational domain should be selected according to the best practice guideline. A building with height H may have a minimal influence if its distance from the region of interest is greater than $6-10H$ [17].

All buildings within at least a 150 m diameter were included in the developed CFD model (Refer Figure 4 and Figure 5).

4.3.2.2 Top of the Computational Domain

The top of the computational domain should be at least $5H$ away from the tallest building with height H [17].

In order to avoid artificial flow over the building, $15H$ is used in this study where H is the building height.

4.3.2.3 Mesh Sensitivity Analysis

Based on a mesh sensitivity assessment, 17,861,799 polyhedral cells were used to cover the computational domain. A minor accuracy benefit could be gained if the number of cells was increased to more than 18 million. On the other hand, significant computational time is saved for the 17,861,799 cells scenario.

In general, the grid resolution should be as high as the computing powers permit.

4.3.3 Discretization

The software package utilised in the current CFD analysis is the commercially available code ANSYS-Fluent [14]. The CFD model solves continuity and momentum in the computational domain to predict the airflow at and around the project site.

- The quality of the mesh is a critical aspect of the overall numerical simulation, and it has a significant impact on the accuracy of the results and solver run time.
- For the current analysis, polyhedral elements with a total number of 17,861,799 nodes were used to cover the external (outdoor) and the internal (indoor) computational domain. Mesh density is shown in Figure 7. Polyhedral cells are especially beneficial for complex geometries including site topography and can handle recirculating flows and may provide more accurate results than even hexahedra mesh. For a hexahedral cell, there are three optimal flow directions which lead to the maximum accuracy while for a polyhedron with 12 faces there are six optimal directions which, together with the larger number of neighbors, lead to a more accurate solution with a lower cell count. It is also worth mentioning that the development of hexahedral elements for real and complex built environment is challenging.

The following techniques were used for discretization:

- A second order numerical scheme for discretization of pressure and momentum to obtain more accurate results.
- A Realizable k -epsilon turbulence model was used for all analysed cases due to the computational time advantages and model capability to capture flow separation and circulation.
- The solution is also combined with a wall function to avoid using very fine elements near the walls.
- An iterative procedure was used to estimate the air velocity in terms of three directions, pressure profile and turbulence parameters.

Figure 8 shows that the normalised residuals of continuity for the simulation were reduced by four while the normalised residuals for x -, y -, and z -velocity, k and ϵ were reduced between six and eight orders of magnitude demonstrating a valid numerical solution.

4.3.4 CFD Results and Discussion

4.3.4.1 General Flow Characteristic

The CFD model was used to model the following wind directions: North; Northeast; East; Southeast; South; Southwest; West and Northwest.

Sample results for three prevailing wind directions are shown in Figure 9 to Figure 11. The results show mean airflow velocities through a two-dimensional section at 1.5 m (typical chest level) above the ground. Velocity magnitudes are plotted on a colour coded scale between 0 and 2.5 m/s. Dark blue represents still conditions at 0 m/s and red represents the strongest wind speed.

One can see that the CFD model captures the fluid flow characteristics in significant details. Wind is approaching the site from the given wind speed and from the given wind direction as per the given boundary conditions. Wind is then accelerated near building edges, channelled between buildings and stagnated and/or recirculated behind the buildings.

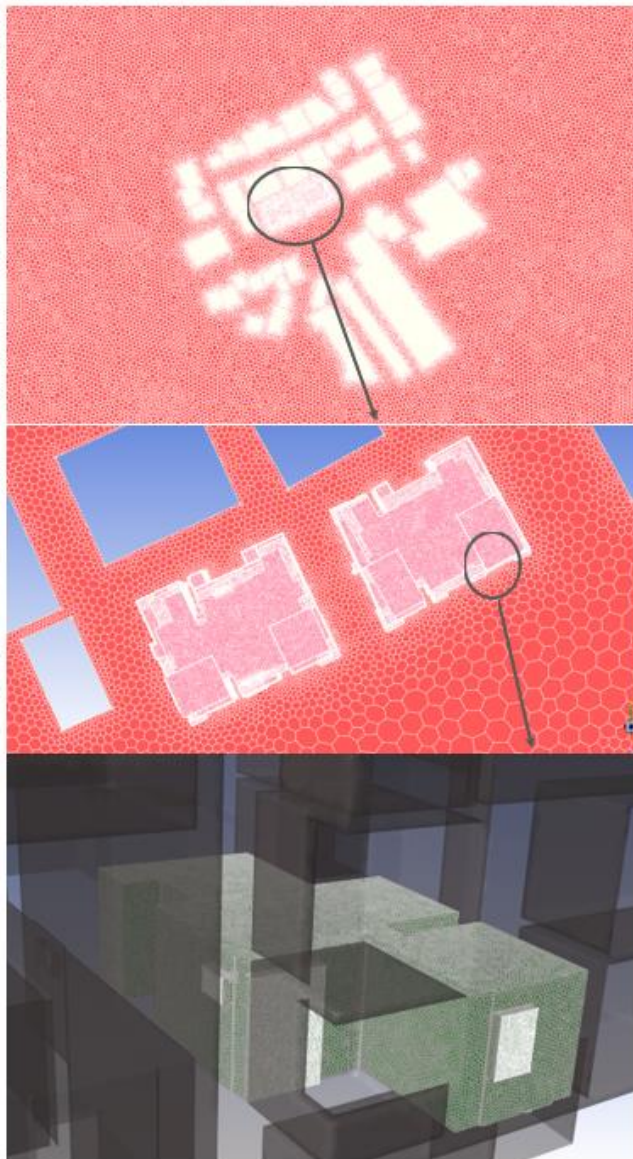


Figure 7: Mesh Density for Selected Unit.

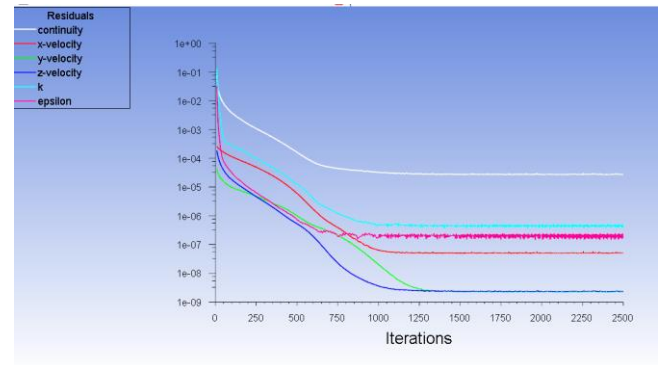


Figure 8: Scaled Residual History.

4.3.4.2 Detailed Flow Characteristic

This study deems an apartment to have adequate natural ventilation if it shows at least three air changes per hour, taking into accounts all analysed wind directions and associated mean wind speed probability.

Sample results for the approaching northeast wind direction are shown in Figure 12. Figure 12 shows mean airflow velocities through a typical chest level above the ground. Velocity magnitudes are plotted on a colour coded scale between 0 and 0.5 m/s and 0 - 0.1 m/s respectively for ease of interpretation. Dark blue represents still conditions at 0 m/s and red represents the strongest wind speed. The following conclusions can be reached from the above figure:

- The proposed openings and indentations demonstrate reasonable airflow distribution due to the location of windows in different pressure regions.
- This study deems airflow to be “reasonable” if the apartment satisfies the minimum air changes per hour requirements and demonstrate good flow from room to room without excessive short circuiting.
- The assessment allows for average mean speed and mass flow calculations at all openings. For example, Unit 1 will experience a maximum wind speed 0.275 m/s and the predicted air changes per hour for the NE wind direction is **5.5**.

The above procedure is repeated for all apartments. The predicted air changes per hour for many analysed apartments are well above the minimum 3 air changes per hour requirements. These units can, therefore, satisfy the ADG requirements without relying on purely wind driven air.

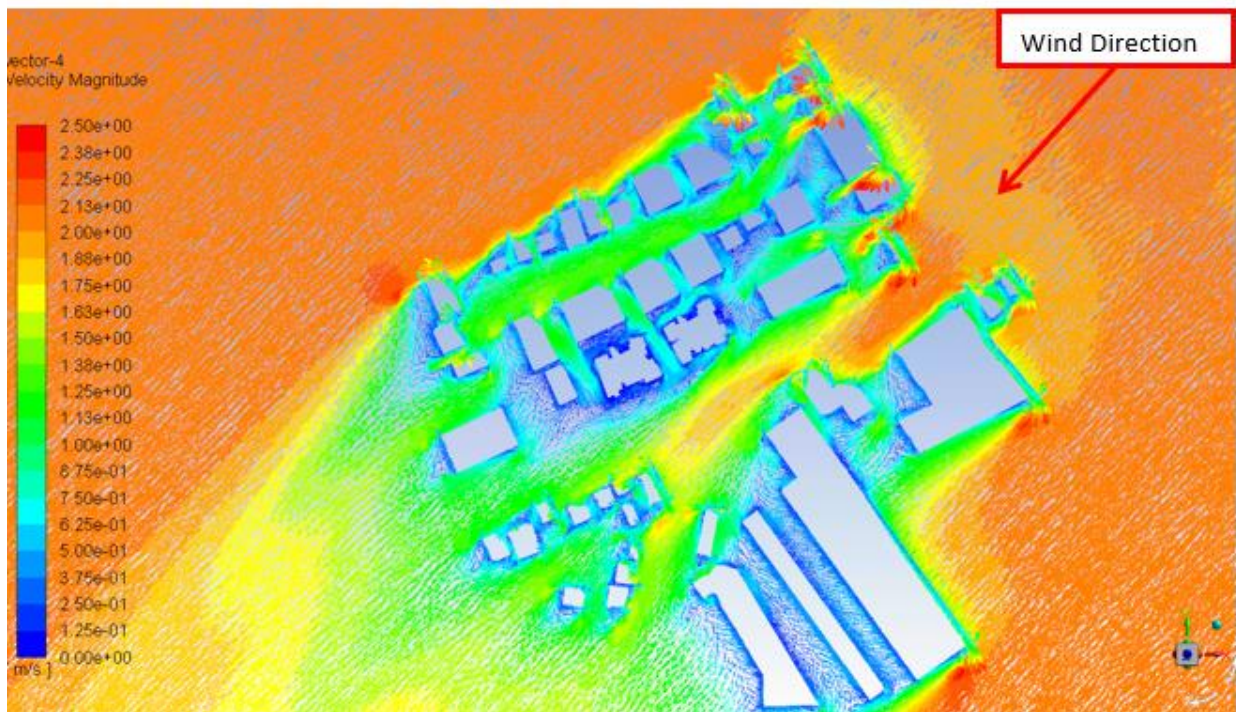


Figure 9: North East Flow (m/s) – Summer Wind.

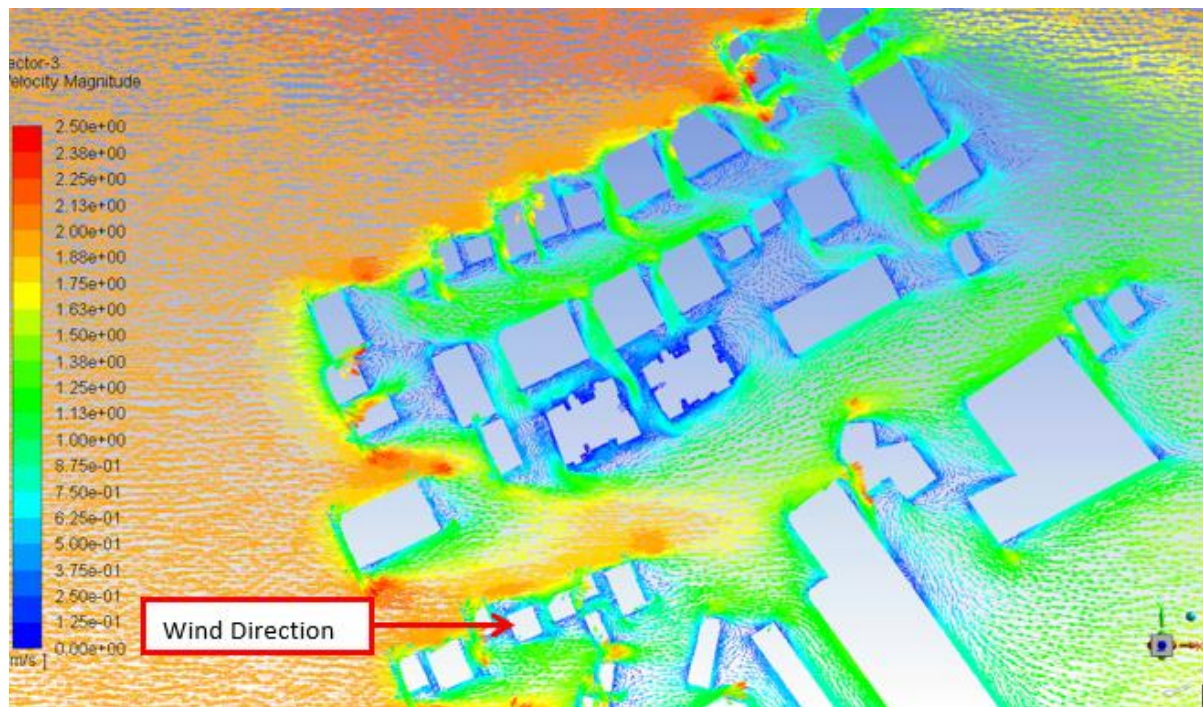


Figure 10: West Wind (m/s) - Winter Winds.

Taking into account all analysed wind directions and mean wind speed exceedance probability for each wind direction, the average air changes per hour is higher than 3 for all analysed units when the 10 m height approaching mean wind speed is 2 m/s. Sample results for selected compliant units are shown in Table 1.

The frequency of wind speeds exceeding 2 m/s obtained from the nearby weather station was high, at approximately 94%. The average air changes per hour were increased between 2-3 times of that in Table 1 when taking all wind directions and mean wind speed probability occurrence into consideration.

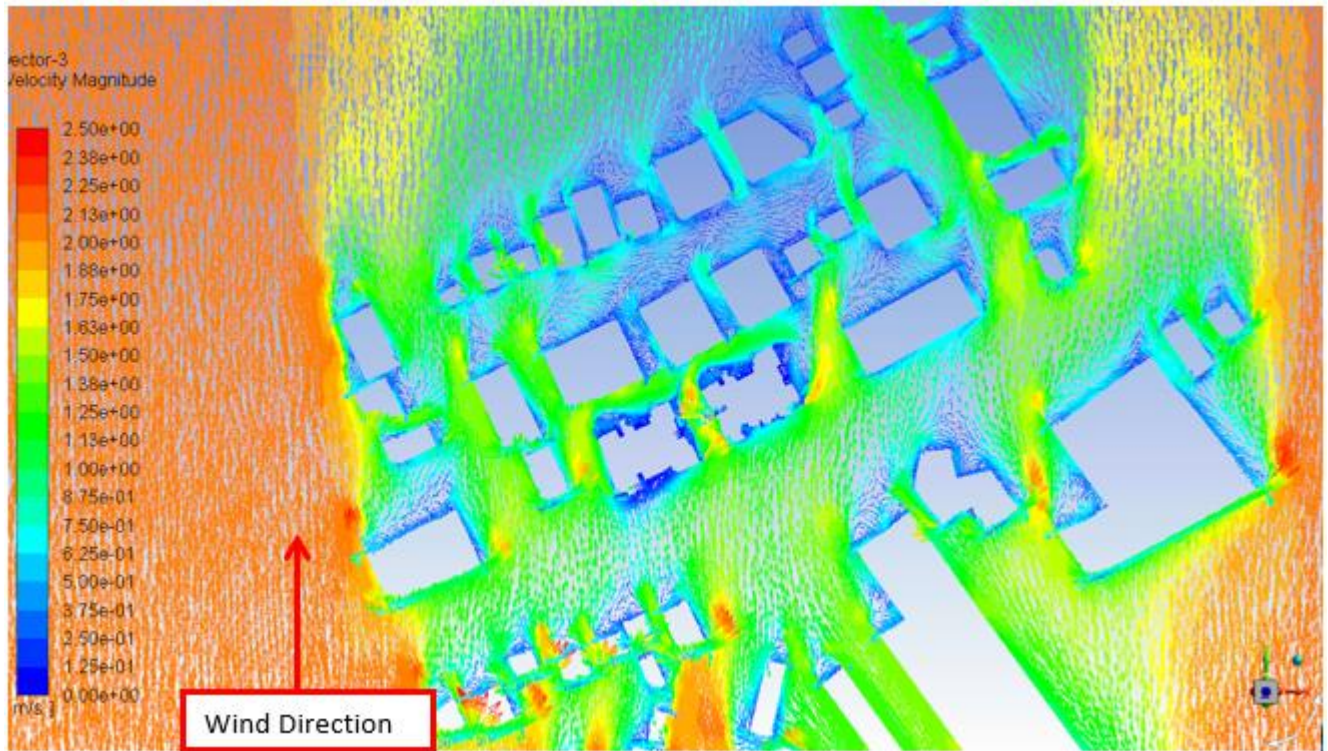


Figure 11: South Wind (m/s) – All Year Around Winds.

Table1: Air Changes Per Hour through Modelled Apartments – Approaching Mean Wind = 2 m/s at 10 m above Ground

Apartment	Wind Direction								Annual Average
	N 0°	NE 45°	E 90°	SE 135°	S 180°	SW 225°	W 270°	NW 315°	
Type 1A	13.0	5.5	3.4	5.1	10.6	3.8	3.4	2.8	6.1
Type 2A	8.7	3.8	2.5	5.5	3.7	14.1	3.5	5.6	5.6
Type 3A	3.3	5.2	11.5	8.3	3.8	12.1	5.4	2.1	5.5
Type 4A	7.6	0.8	1.4	3.9	0.5	4.8	10.5	11.3	5.5
Type 5A	1.0	4.4	10.7	16.0	9.3	10.3	1.3	6.3	6.9
Type 1B	14.2	15.3	10.4	9.9	3.8	1.8	5.4	7.0	8.3
Type 2B	7.9	12.8	25.4	4.2	9.0	13.1	4.4	9.4	9.8

5. SUMMARY OF THE PROPOSED PROCEDURE

1. Qualitatively assess the natural ventilation for all dual aspect and cross through apartments. These units are deemed to be cross ventilated if the overall depth of a cross-over or cross-through apartment is less than 18m, measured glass line to glass line. The effective open area for the inlet and outlet sides should be approximately similar. Compliance with the adopted ADG is achieved if at least 60% of the apartments are naturally cross ventilated in the first nine storeys of the building.

2. Introduce building indentations and façade articulations to encourage pressure differences between various openings for single sided apartments.
3. Analyse the local weather data and prepare detailed wind probability data for the project site.
4. Quantitatively assess the ventilation rate for these single sided apartments. The assessment must take into account the pressures differences caused by approaching wind pressure, local wind climate and interaction with the surrounding built environment and external pressure gradients on the

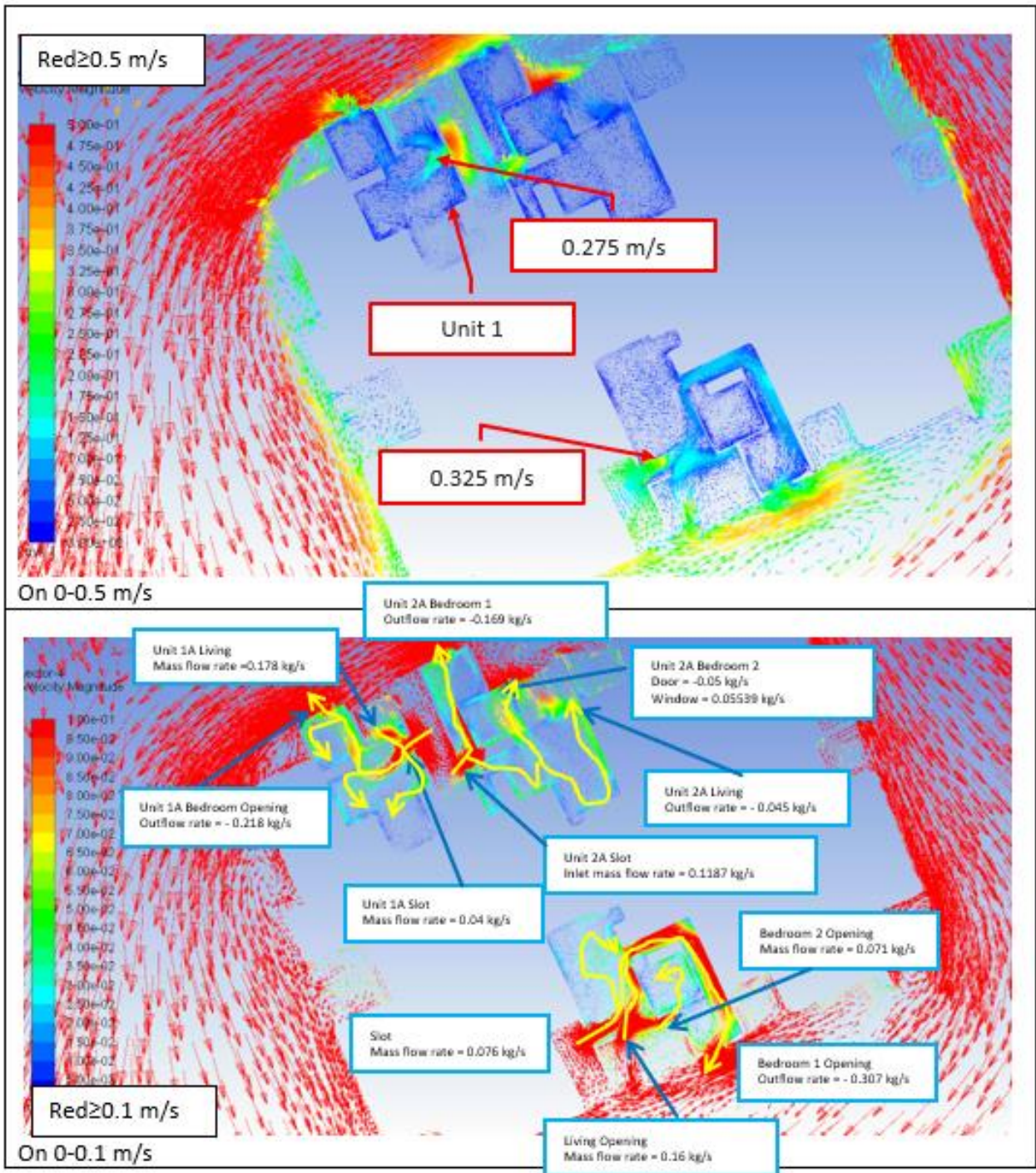


Figure 12: Velocity Vector Coloured by Velocity Magnitude (m/s) – North East Wind, Approaching Wind = 2 m/s.

5. Calculate the number of apartments located in significantly different pressure regions, which can achieve at least 3 air changes per hour, taking into account all wind directions and localised wind speeds.
6. Ensure that compliance with the ADG is achieved based on the qualitative assessment, of the dual aspect/cross through apartments and quantitative assessment of non-dual aspect apartments with openings located on different pressure regions.
7. In consultation with the project team and based on the CFD results for the base case scenario, run design modifications (modify indentation dimen-

sions, opening size, etc.) if the pressure difference between openings is not enough to provide appropriate ventilation rate and ensure compliance with the adopted design guide.

6. CONCLUSIONS

A reliable procedure is presented to assess natural cross ventilation in single sided apartments, and advise on compliance with national and/or international design guidelines utilising a combined outdoor-indoor flow Computational Fluid Flow (CFD) analysis integrated with a localised weather data.

This study has demonstrated that natural cross ventilation for indentation apartments can be achieved when single sided apartments are designed to have openings (windows and sliding doors) in different pressure regions, rather than relying on purely wind driven.

Effective air circulation for a number of analysed apartments is achieved without having indentations with a width to depth ratio of 2:1. The proposed methodology in the current study is recommended if a project cannot satisfy the building indentations (2:1) width to depth ADG requirement due to the planning and design issues.

The study addressed the orientation of the building, the configuration of apartments, local wind climate and interaction with the surrounding built environment, external pressure gradients on the building indentations and/or any other facades articulation and their potential driving force upon natural ventilation.

The paper also discussed some of the parameters that have influence on the numerical results accuracy.

The presented tool helps to optimise the configurations of single sided apartments during the concept design stage to enhance fresh air movements through an apartment, and create a comfortable indoor environment. The CFD tool can also have multiple "downstream" applications, for example the same model could be used to examine thermal comfort, air quality (pollutant transport) issues, wind-driven rain ingress, wind induced noise, fire simulation, etc.

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