Designing for Natural Ventilation in Tall Residential Buildings

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Kevin Peddie

Biography

Kevin Peddie graduated from the University of Sydney with Bachelor of Engineering (Aeronautical) (Hons I). Since joining Windtech Consultants, Kevin has undertaken numerous wind tunnel studies in Australia, South-East Asia and the Middle East. Kevin has substantial experience in the analysis of wind effects using wind tunnel modeling. Kevin has a particular interest in the modeling of natural ventilation in building.

Kevin has carried out numerous natural ventilation studies for both commercial and residential developments. Through these studies, he is able to assess the effectiveness of proposed opening locations and sizes for natural ventilation performance and advise regarding optimal openings to achieve adequate natural ventilation performance for the development.

Tony Rofail

Biography

Tony has over 20 years' combined experience as both researcher and consultant in wind engineering. Tony Rofail is a director of Windtech and has been with the company since 1991. Since that time he has been Windtech's principal consultant. Tony has undertaken and supervised over 1000 wind engineering studies including wind tunnel investigations for various high-rise buildings, large roof and stadium building projects throughout Australia and in New Zealand, China, Hong Kong, Taiwan, India, Malaysia, Singapore, Thailand, The Philippines, Indonesia, United Arab Emirates, Kuwait, Bahrain, Qatar, Saudi Arabia, Lybia and Jordan.

Tony is on the Wind Loading sub-committee of the Australian and New Zealand Standards and was on the executive committee of the Australasian Wind Engineering Society (AWES) between 1998 and 2006. While on the AWES committee in 1998-1999, Tony was responsible for the preparation of the draft AWES Quality Assurance Manual for wind tunnel studies of dynamic overall wind loads on structures. Tony is a corporate member of the Institution of Engineers, Australia.

Abstract

Natural Ventilation is an important part of achieving energy efficient design in many climate zones. This issue has surfaced recently with the increased awareness in the community of climate change and of mankind's impact on the environment. Natural Ventilation is particularly applicable to residential buildings, where there is the greatest enable the occupants to reduce reliance on mechanical systems. Recently, greater emphasis has been placed on natural ventilation in codes and planning policies. Traditionally natural ventilation has been applied to low-rise buildings. Now however, the application of natural ventilation principles to tall buildings is being embraced by both architects and developers. Tall buildings have the advantage of being able to generate higher pressure differentials across the dwelling, making it potentially easier to achieve thermal comfort for occupants by means of natural ventilation. Today many planning policies provide guidelines that stipulate the need for adequate natural ventilation in residential buildings. Experience has shown that by incorporating natural ventilation principles into the design at an early stage, the risk of non-compliance can be significantly reduced. Wind tunnel testing is a powerful tool for the modelling of natural ventilation performance in a building.

This paper presents the natural ventilation principles that are applicable to tall buildings as well as a number of case studies. These include strategic design options to incorporate natural ventilation at a late stage in the design process and still achieve a successful design outcome. It also looks at the effect of designing a tall building with natural ventilation considered at an early stage in the design process. The codes and regulations associated with natural ventilation have a significant impact on the design for natural ventilation. Within Australia, two main planning policies stipulate what is considered a naturally ventilated building. However some of the aspects of these planning policies are too restrictive and in some cases it would be impossible to achieve compliance due to site constraints. With thoughtful design and wind tunnel testing it has been possible to demonstrate equivalence in performance whilst maintaining compliance with provisions without compromising deign excellence.

Keywords:
Natural Ventilation, Residential, Case Studies

1. Introduction

In recent times, the apparent potential to improve the energy efficiency of existing and future building for sustainable design has been realised, with many designs now focusing on the carbon footprint both during the construction phase and also once the building has been completed. This paper looks at the implementation of natural ventilation in residential developments. Further to this, the paper will discuss three cases studies, each currently at different stages of development. A detailed analysis has been undertaken by Windtech Consultants to determine the natural ventilation performance characteristics for each of the residential apartments of the developments using wind tunnel testing. Wind tunnel testing is able to measure the potential for natural ventilation depending on the pressure differential generated at each opening of an apartment. The overall performance however, is dependent on a large number of contributing factors which include: the development's exposure to the prevailing breezes; the effect of the surrounding buildings on the development; overall building massing; location, efficiency, orientation and sizes of openings and façade design and local conditions.

The ability to harness the natural elements for potential gain has long been an important part of building design, however some elements are more predictable than others. Sunlight for instance is a known entity with its' location throughout the day and year for a given geographical location able to be determined, with the unknown factor being the presence of cloud cover or lack there of. This enables appropriate design parameters to be established which are able to help harness the suns light for solar gain. Wind conditions however are a far more variable entity. Conditions vary from site to site as well as from year to year, day to day and minute to minute. Trends are able to be established from recorded meteorological data for wind directions and percentage of occurrence and wind speeds.

Principles for designing for natural ventilation is widely discussed with ideal configurations for residential apartment layouts generally detailed in local planning requirements to obtain acceptable levels of in-principle natural ventilation. These ideal configurations are usually overly simplified and areas such as surrounding buildings, the building profile and local climate usually neglected, yet are significant influences in this process.

1.1 Applicability

The ability for any development to be able to utilize natural ventilation in the overall design is firstly governed by one large component, the local climate at the development site. For any development to be able to achieve natural ventilation, firstly the climate must be such that the occupants of the building will wish to open their windows and doors to the outside elements. If conditions are too hot or cold, the occupants will simply choose for all openings to remain closed and utilize available mechanical systems. ANSI/ASHRAE 55-2004 provides a method to determine the suitable thermal conditions for a naturally ventilated space. This associates the outdoor climate with two sets of occupant acceptability based on a database of 21,000 measurements. This provides an 80% and 90% acceptability range based on the external climate, the ability for the occupants to be able to control operable windows and to adjust clothing according to the thermal conditions. Tables 1 and 2 show the required indoor temperature limits for natural ventilation for Sydney, Australia, at 9am and 3pm, where the three case studies discussed later are located. Also presented, in Tables 1 and 2, are the mean maximum and minimum temperatures during the day for Sydney. It can be noted from the ranges that occupant acceptability vary throughout the year and are limited especially during the winter months when a naturally ventilated space would not be considered acceptable by the occupants of the building.

Local climates vary considerably depending on the location around the world, and as noted above, this location essentially is the underlying governing factor for whether natural ventilation should be first considered. This does not eradicate the ability to utilize natural ventilation, but determines periods when single or mixed-mode ventilation would be required.

Table 1. Indoor Operative Temperature Limits for Sydney 9am (ASHRAE Standard 55-2004)

9am	Mean Monthly Outdoor Temperature (˚C)	Mean Daily Minimum Temperature (˚C)	Mean Daily Maximum Temperature (˚C)	80% Acceptability		90% Acceptability	
				Min (˚C)	Max (˚C)	Min (˚C)	Max (˚C)
January	22.4	18.8	26.4	21.3	28.2	22.3	27.3
February	22.3	19.0	26.3	21.2	28.2	22.3	27.3
March	21.1	17.5	25.2	20.9	27.8	21.9	26.9
April	18.2	14.1	22.9	20.0	26.9	21.0	26.0
May	14.6	10.9	20.0	18.9	25.8	19.9	24.9
June	11.9	8.6	17.6	18.0	25.0	19.1	24.1
July	10.8	7.1	17.0	17.7	24.7	18.7	23.7
August	12.5	8.1	18.3	18.2	25.2	19.3	24.3
September	15.7	10.3	20.5	19.2	26.1	20.3	25.3
October	18.4	13.1	22.5	20.0	27.0	21.1	26.1
November	19.9	15.3	24.0	20.5	27.4	21.6	26.5
December	21.6	17.5	25.7	21.0	27.9	22.1	27.1

Table 2. Indoor Operative Temperature Limits for Sydney 3pm (ASHRAE Standard 55-2004)

3pm	Mean Monthly Outdoor Temperature (˚C)	Mean Daily Minimum Temperature (˚C)	Mean Daily Maximum Temperature (˚C)	80% Acceptability		90% Acceptability	
				Min (˚C)	Max (˚C)	Min (˚C)	Max (˚C)
January	24.8	18.8	26.4	22.0	28.9	23.1	28.1
February	24.8	19.0	26.3	22.0	28.9	23.1	28.1
March	23.9	17.5	25.2	21.7	28.6	22.8	27.8
April	21.7	14.1	22.9	21.0	28.0	22.1	27.1
May	19	10.9	20.0	20.2	27.2	21.3	26.3
June	16.6	8.6	17.6	19.5	26.4	20.5	25.5
July	16.1	7.1	17.0	19.3	26.3	20.4	25.4
August	17.2	8.1	18.3	19.7	26.6	20.7	25.7
September	19	10.3	20.5	20.2	27.2	21.3	26.3
October	20.7	13.1	22.5	20.7	27.7	21.8	26.8
November	22.1	15.3	24.0	21.2	28.1	22.2	27.2
December	23.9	17.5	25.7	21.7	28.6	22.8	27.8

1.2 *Benefits of Natural Ventilation*

The main reason for the global market to utilise natural ventilation in design essentially stems from the overwhelming benefits. The people who gain from these benefits vary from society, the developer, the owner and the occupant.

The most obvious benefit of natural ventilation is the energy efficiency of the system to supply fresh air to a specified space. This saving is essentially due to the reduction in reliance on mechanical HVAC systems for cooling/heating and ventilation for the occupants. Previous studies by Carnegie Mellon University (CBPD/ABSIC BIDS) as indicated in Figure 1, shows the cost benefit associated with natural ventilation and mixed-mode systems. Eight studies of office buildings were undertaken and it was found that for an initial upfront cost of $1,000/employee for new developments and $3,400/employee to retrofit an existing building, an annual energy cost saving of $110/employee, health cost saving of $60/employee and annual productivity gains of $3,900/employee was able to be realized. This is a substantial cost saving in both the running of the building and also the running of any business within the building.

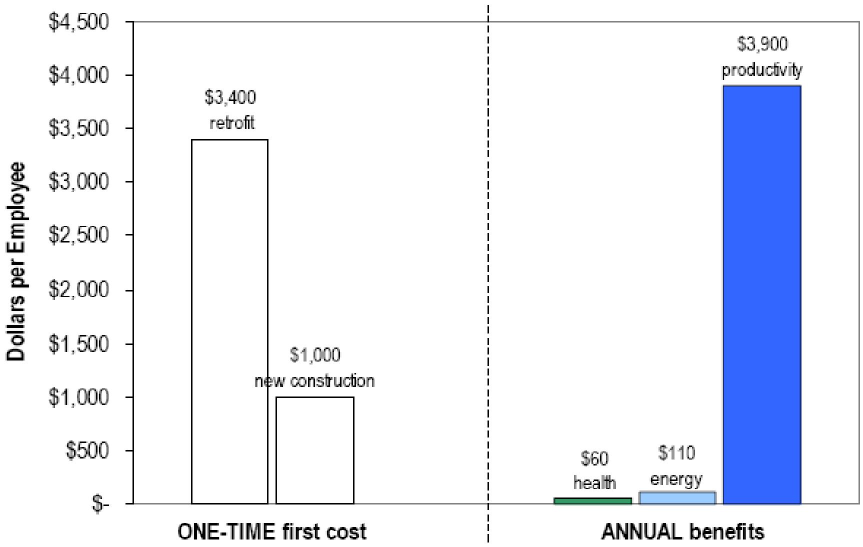

Figure 1. Costs and Benefits of Mixed-Mode Conditioning and Natural Ventilation [EBIDS]

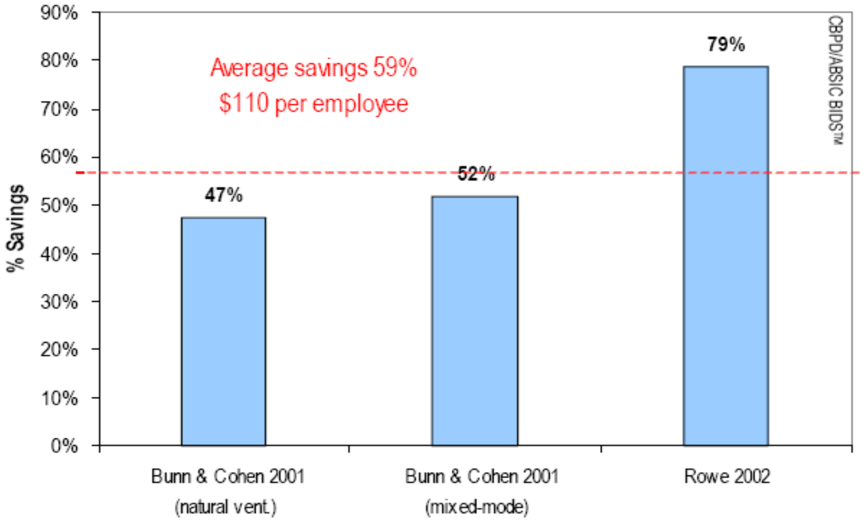

Figure 2. Annual HVAC Energy Savings from Mixed-Mode and Natural Ventilation [EBIDS]

As can be seen from Figure 1, the largest cost benefit associated with a building designed for natural ventilation is the increased productivity of the occupant. It has been demonstrated that a naturally ventilated building results in over 70% reduction in absentees of employees, between 40% and 60% reduction in Sick Building Syndrome (SBS) symptoms, improvement in test results and a perceived increase in productivity [EBIDS].

Figure 2 shows from three studies conducted, the measured percentage saving's fro utilising mixed-mode HVAC systems for ventilation. The use of natural ventilation to nullify or supplement a HVAC unit clearly shows substantial cost savings are available.

2. Natural Ventilation Criteria

A naturally ventilated building is dependent on numerous aspects, such as the size and use of a space, the number of occupants and what materials exist in the space. Standards including AS1668.2-2002 and ANSI/ASHRAE 62.1-2004 provide criteria for air quality of a space with the criteria dependent on those abovementioned parameters. Generally for residential applications, depending on the number of people expected to be present in the room, the above standards recommend that for sufficient air quality a minimum of between 1 and 2 air changes of the space per hour is required. It is also noted that for mechanical systems this requirement is generally quite higher. This is due to the quality of the air supplied by natural ventilation, which replaces the internal air with fresh external air.

Guidelines are presented in ANSI/AHSRAE 55-2004 for the thermal comfort of an occupant within a ventilated space. It has largely been documented that the flow of air over a person's skin generates a cooling sensation which reduces the perceived ambient temperature. The minimum air speed required to generate some form of cooling sensation is dependant on the climate for the area. In the case of Sydney, a minimal sensory cooling of 2ºC can be achieved for an internal flow greater than 0.4m/s. It is also reported that an upper limit of approximately 1m/s for office areas is recommended, as above this speed, papers will start to rustle and the discomfort may be experienced due to the air flow, however areas where this is not a concern would benefit from slightly higher air speeds.

Other statutory planning requirements include criteria based on the percentage of apartments in the development which are required to meet the abovementioned criteria for the development to be considered naturally ventilated.

3. Wind Tunnel Testing Methodology

Wind tunnel modeling for natural ventilation is a reliable way to accurately model the wind flow around a development as well as the pressure gradients across an internal space or dwelling. It is able to correctly account for the effects of land topography, surrounding buildings and the approaching wind speed and turbulence intensity profile. Natural ventilation is measured by testing a scale model of the development within a boundary layer wind tunnel and with all openings to the development monitored by pressure sensors. This is then tested for between 16 and 36 wind directions in conjunction with the appropriate wind climate for the area and in order to scale the results obtained. An example of a model in the wind tunnel is shown in Figure 3.

From the measured wind tunnel results, the wind driven ventilation flow rate is able to be determined from Eq1. based on Aynsley *et al* (1977). This is able to be converted to air changes per hour depending on the volume of the space.

$$Q = \left(\frac{\left(C_{p_1} - C_{p_{n+1}}\right) v_z^2}{\frac{1}{C_{d_1}^2 A_1^2} + \frac{1}{C_{d_2}^2 A_2^2} + \frac{1}{C_{d_3}^2 A_3^2} + \dots + \frac{1}{C_{d_n}^2 A_n^2}} \right)^{\frac{1}{2}} \quad (1)$$

Where Q is the flow rate (m^3/s).

C_{p_n} is the measured pressure coefficient at opening n.

v_z is the velocity at the reference building height (m/s).

C_d is the discharge coefficient through the opening.

A is the area of the opening.

Figure 3. Wind Tunnel Model

4. Case Studies

Three case studies are presented based on three residential developments located in Sydney. The first development is located in Parramatta and is a 25 storey building currently undertaking the final design process. The second development is located in Chatswood and is a 42 storey building which is about to commence construction. The last building is located in Parramatta and is a 17 storey building which was completed several years ago. All three buildings are located in New South Wales and are required to demonstrate that over 60% of the residential apartments satisfy the natural ventilation requirements for the overall development to be considered naturally ventilated.

4.1 Macquarie Place, Parramatta

This development is a 25 storey residential building consisting of 367 apartments located in Parramatta in the greater western Sydney area. The development is shown in Figure 4. Residential apartments are situated on all aspects of the building with the majority along the eastern and western aspects. Prior to investigating the natural ventilation performance of the development Windtech were able to meet with the architects of the development to discuss the current design, including the internal layout, to improve the chances for natural ventilation. The design consisted of four setbacks in the façade (two on the eastern and two on the western aspects) which were designed to allow daylight into the internal corridor area and also provide areas of pressure differential for the adjoining apartments. The predominant wind directions for the warmer months of the year occur from the southerly and north-easterly winds and would be the governing factors. It was recommended that due to the large number of single aspect apartments, that the design be altered such that each apartment consisted of a stepped profile, with one opening to the apartment located on the building façade and the other located within a recessed balcony at least 2 metres deep. Further to this, the architects allowed for additional air vents which would be located at the back of the apartments and extend to the roof of the building to provide additional ventilation as required.
A model of the development at 1:300 scale was placed in a surrounds model which incorporated the surrounding buildings and topographical effects for 400m in all directions. This was then placed in Windtech's boundary layer wind tunnel and tested for 36 wind directions. Pressure sensors were placed at all of the proposed openings for the residential apartments.

The results from the analysis of the wind tunnel testing of the development indicated that due to a late design change whereby the western setbacks in the façade were either not utilised or reduced in size, only 52% of the apartments achieved the requirements of at least 2 air changes per hour (ACH) and a minimum internal flow rate of 0.4m/s for thermal cooling. Further analysis was then undertaken with the inclusion of proposed air vents located at the rear of the apartments. These air vents were recommended to be $1m^s$ in area to maximize the flow efficiency and should be acoustically lined and include fire baffles. One way louvres were also recommended at the opening to the apartment to ensure that the air flow entered the apartment through the windows (positive pressure region) and travelled out through the air vent. The air vent was to extend to the roof of the development whereby due to the location and design would generate a negative pressure region (Rofail and Aurelius, 2004). As the façade pressure on a building varies with height, based on the measured pressures over the height of the façade, it was recommended that three vent shafts be included for each apartment type to ensure upper level apartments did not reduce or impede the flow for the lower level apartments.

Figure 4. Macquarie Place, Parramatta

With the inclusion of the abovementioned air vents for 5 of the apartment types on each level, 74% of the residential apartments were able to be shown to satisfy the requirements for natural ventilation.

4.2 7 Railway Street, Chatswood

This development is a 42 storey residential building consisting of 295 apartments located within the Chatswood CBD, north of Sydney. The development, which is shown in Figure 5, is a rectangular shaped building with private balcony area for the apartments located on the northern, eastern and western aspects. The development is surrounded by buildings of a similar height. It is also located adjacent to the railway line and as such has limitations on the design such as window opening sizes and balcony areas due to the proximity to the railway corridor for safety reasons. This has limited the southern aspect of the building to consist solely of awning windows with a maximum opening distance of 300mm. During the earlier design stages of the development recommendations were made by Windtech to the client to help ensure that the ability for the development to satisfy the requirements for natural ventilation. This was found to also satisfy the direct solar access requirements for the development. Other limitations included the restriction to potentially utilize air vents at the top or mid-way up the tower. This was due to the very intricate design which did not allow for any additional space for vent shafts. As such, the façade detailing would be vital in ensuring that natural ventilation could be achieved.

Figure 5. Railway Street, Chatswood

A model of the development at 1:400 scale was placed in a surrounds model which incorporated the surrounding buildings and topographical effects for 500m in all directions. This was then placed in Windtech's boundary layer wind tunnel and tested for 36 wind directions. Pressure sensors were placed at all of the proposed openings for the residential apartments.

The results of the analysis indicated that the residential apartments would be able to satisfy the requirements for air quality with more than 2 ACH achieved. However it was noted that the air speed through the living zone of the apartment was limited by the awning windows on the southern aspect of the development as well as the location of some opening locations to ensure air flow occurred throughout the entire apartment. Recommendations were made to the client for the inclusion of additional awning windows along the southern aspect to increase the effective opening area for this aspect of the apartments. Further to this, openings to some of the living spaces of the development were recommended to be located on different aspects of the stepped façade to improve the internal flow effectiveness. With the inclusion of these recommendations into the final design, it was found that 61% of the residential apartments would be able to achieve natural ventilation for both the requirements of air quality and thermal comfort. Wind tunnel testing enabled the development to incorporate natural ventilation at a later design stage. The limitations due to the fixed design of other elements limited the options for alternative design direction. However the effective use of stepping the façade of the single aspect residential apartments by more than 2 metres, and due to the predominant winds approaching the site at an obtuse angle enabled a sufficient pressure differential to be established between openings.

4.3 Gallery, Cowper Street, Parramatta

This development is a 17 storey residential building consisting of two towers with a total of 250 apartments located in Parramatta, in the greater western Sydney area. The development, shown in Figure 6, consists of two rectangular shaped buildings linked on the lower levels via a connecting bridge area with residential apartments facing towards the east and west of the development.

A model of the development at 1:200 scale was placed in a surrounds model which incorporated the surrounding buildings and topographical effects for 250m in all directions. This was then placed in Windtech's boundary layer wind tunnel and tested for 36 wind directions. Pressure sensors were placed at all of the proposed openings for the residential apartments.

Figure 6. Cowper Street, Parramatta

Initial analysis indicated that the design would not satisfy the requirements for natural ventilation due to the design of the façade and window opening sizes. In consultation with the client the recommendation and analysis for the use of air vents was proposed, similar to that mentioned in Section 4.1. With the inclusion of air vents for the single aspect residential apartments, the apartments were able to satisfy the requirements for natural ventilation.

Further to this, since the development was bas completed, full-scale testing of the effectiveness of the roof air vents has been undertaken. This involved using smoke modeling to measure the air flow velocity at the openings of the available apartment (B601). The apartment tested was a single aspect two bedroom apartment which utilized an air vent located in the main bedroom area to enhance ventilation. The apartment was located on Level 6 on the eastern aspect. Measurements were taken with all openings closed except for the roof vent and opening being measured. A comparison between the results from the wind tunnel study and the full scale measurements are indicated in Table 3. The comparison for the wind tunnel analysis has been made for three mean wind speeds (recorded at the local weather stations over the period of testing) which have been converted to the site location. The recorded mean wind speeds varied between 28km/h at the start of testing to 20km/h towards the end of the full scale testing.

Table 3. Full-Scale Test Results of Wind Speeds at the Balcony Doors Compared to Wind tunnel Test Results

Opening	Full-Scale Measurement	Wind Tunnel Measurement
Main Bedroom	0.7m/s - 0.9m/s	0.7m/s – 1.0m/s
Second Bedroom	1.0m/s – 1.2m/s	0.8ms/ - 1.1m/s
Living Room	0.6m/s – 1.0m/s	0.8m/s – 1.1m/s

It was noted during the testing that the main bedroom was tested towards the end of the period when the wind was recorded to have eased. Ideally, onsite measurements of the wind speed and direction would enable a far more reliable analysis to be undertaken as the exact wind conditions at the time of the test would be able to be recorded while the available data was only in half hourly intervals.

5. Conclusion

The design of existing and future buildings has been heavily shifted towards minimizing the overall carbon footprint of the building both during the initial start-up costs and in respect of the associated long term running costs. A building may be solely naturally ventilated or a combination of mixed-mode ventilation. This is predominantly determined by the climate where the development is located as to how effective, if at all, this practice can be.

The design of residential apartment development to incorporate natural ventilation is something which can be undertaken effectively with substantial gain for numerous people closely and loosely associated with the development. Through the discussed case studies it was observed that early design intervention in understanding the environment in which the development is to be located in order to effectively harness these elements can have substantial end gains for the natural ventilation performance.

Full scale analysis has indicated that the modeling of natural ventilation through wind tunnel testing has produced comparable results when compared analysed in reference to full-scale measurements.

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