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Procedia Engineering 00 (2017) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

Optimization of wind tower cooling performance; a wind tunnel study of indoor air movement and thermal comfort

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Abstract

Wind tunnel testing and thermal comfort simulations were conducted to explore the performance of a wind-tower in a typical, medium-density apartment building located in subtropical Sydney. The research design consisted of three phases; first, wind tunnel experiments measured pressure distributions over the surface of a four-storey apartment building model scaled at 1:100. Secondly, hourly indoor air velocities were predicted for the six warmest months in Sydney using the Typical Meteorological Year 2013. Finally, thermal comfort simulations evaluated the comfort cooling potential of the wind towers. Results indicate that, during Sydney's warm hours (≥23°C), elevated air speeds resulting from the wind-tower improved in indoor comfort by 1725.8 degree hours (SET*) compared to the default design relying on through-window cross ventilation under the same conditions.

Peer-review under responsibility of the organizing committee iHBE 2016.

Keywords: natural ventilation; wind tower; wind tunnel; indoor air speed; thermal comfort

1. Introduction

Heating and cooling account for 40% of household electricity end-use in the Australian household sector, and within that 40% a large share is attributed to comfort cooling which is dramatically increasing [1]. Australia's National Climate Change Adaptation Research Facility reports that Australian cities would encounter more heat and radiation and less rain over the next fifteen years [2]. Since the building sector is responsible for 40-50% of the

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Peer-review under responsibility of the organizing committee iHBE 2016.

carbon emissions around the world, natural ventilation systems have become the focus of attention to mitigate the hazards resulting from fossil fuel consumptions [3]. During the past decades, studies on the effects of ventilation on the occupants' thermal comfort have reported that increased air movement can offset elevated indoor operative temperature by removal of heat of human body tissue through evaporative and convective transfers [4-8].

The wind tower, as a vernacular natural ventilation technique, has been applied in Persia and Persian Gulf region since 1300 BC [9, 10]. The wind tower or "wind catcher" is a tower mounted on the construction roofline where it captures air flowing at high speeds within the urban canopy layer and channels it down into the living room or the basement of the building for comfort cooling during the warmer months of the climatic year. The wind tower's openings are exposed to the free-stream wind with higher speed, which generates a large pressure distribution over the wind tower. The internal partitions of the tower channel the flow into the occupied interior spaces downstairs [11].

Nomenclature

Cp	mean pressure coefficient
Pm	mean surface pressure
Ps	mean static pressure
Pd	dynamic pressure
ρ	air density
V	exterior mean wind speed
Q	mean mass flow rate
A	area
ΔCp	pressure coefficient differential
Vi	indoor air speed
L	room volume
k	surface roughness
ν	kinematic viscosity
P	perimeter of conduit

1.1. Background of the research

Numerous earlier studies have attempted to evaluate the function and the cooling performance of wind towers. Bahadori [12,13] analyzed the function of wind tower and suggested two new designs of evaporative wind towers. Karakatsanis et al. [14] assessed the wind tower cooling performance with an adjoining courtyard in the building. They concluded that the courtyard could increase the cooling efficiency of the tower. They also noted that the wind direction and the tower's opening configurations play a significant role on the overall efficiency of the wind tower. Roaf [9] carried out field studies in the hot and arid climate in Yadzd, Iran on the thermal performance and the potential of temperature reduction of wind towers. Elmualim [15] reported that the efficiency of wind tower would reduce by increasing the wind direction from normal to tower's opening. Montazeri and Azizian [16] found that the number of wind tower openings was a significant factor in generating the airflow rate inside the duct. They reported that the higher number of openings would lead to less airflow rate. Similarly, Khan et al. [17] presented that one-sided wind tower preformed higher ventilation rate than a multi-sided tower under the optimum direction of a dominating wind. Conversely, in another research on the evaporative wind tower, Hosseinnia et al. [18] concluded that the higher number of internal wet partitions inside the tower could increase the thermal performance of the tower by increasing the evaporation process. The impact of pressure difference between inlet and outlet air on the wind tower efficiency has been noted in Montazeri et al. [19] research.

In a numerical modeling exercise using CFD, MacCabe and Roaf [20] evaluated the effects of height and cross-sectional area of the tower on the adaptive comfort and the thermal environmental performance of simulated vernacular wind towers. The geometry of the wind tower's roof was assessed in a wind tunnel study by Dehghan et al. [21] using three detached models and the results showed that the incline roof could preform more efficiently under the various wind directions compared with flat-roof and curved-roof designs. Calautit and Hughes [22] studied multi-directional commercial wind tower's ventilation performance and found that the wind direction within 45° of the normal to the tower's opening would generate the higher airflow rate compared to more acute wind directions.

1.2. Gaps in the literature

According to fundamental architectural aerodynamics principles, pressure distributions over the building openings are the primary force generating wind-driven ventilation. As a result, the urban morphology, the external design of the building, and the orientation and location of the tower in relation to the base building should all be considered as significant factors affecting the pressure discharge and the indoor air distribution. Furthermore the energy loss inside the tower caused by the duct's bends and its overall length are also important determinants of the wind tower's effectiveness in terms of comfort cooling performance. The existing wind tower literature has mostly relied on either detached wind towers (no building at all) or a tower attached to just one single room, mostly to measure the airflow rate inside the tower duct or the induced airflow at the exit of the tower [15-22]. Architectural aerodynamic principles indicate these abstractions oversimplify the problem because the building form itself is a determinant of the flow around and through the building. There is also room for comparison between wind tower ventilation rate and through-window cross ventilation in the base-case of the building fenestration.

1.3. Research objectives

Responding to these shortcomings in the extant wind tower research literature this study aims to:

- Optimize the wind tower geometry in a medium density residential context.
- Evaluate the ventilation performance of the wind tower in the contemporary Sydney climate context.
- Assess the thermal comfort effects of the wind tower's ventilation performance.

2. Wind tunnel studies

A 1:100 scaled empirical model of a 4 storey apartment building was fabricated to analyze the impact of the exterior and interior design of the tower on the indoor air movement. Wind tunnel experiments in three separate configurations were conducted at Cermak Peterka Peterson (CPP) laboratory in Sydney Australia to measure the surface pressures over the sealed model.

2.1. Boundary layer wind tunnel

The CPP wind tunnel in Sydney has a closed circuit design with internal dimensions of 20 m length, 3.0 m width, and 2.4 m height, with the testing section's roof designed to mitigate blockage effects. A variable frequency fan drives the wind tunnel. The approaching flow processing section was set up with a boundary layer category 2 terrain, as defined in Australian Standard 1170.2 [25]. The tunnel floor was covered by a matrix of roughness elements to generate turbulence and simulate wind flow characteristics approaching the testing section; the boundary layer thickness is up to 1.5 m. Following the processing section, there is a testing section with a turntable of 3.0 m diameter, where the velocity and pressure instrumentation are located. Pressure data processors are mounted underneath the turntable. Experimental data have been collected via a PC-based data acquisition system located outside the tunnel, adjacent the testing section.

2.2. Model design and fabrication

Urban design, building form, dimension, and height all influence pressure distributions over a building [23]. Therefore, to predict the air speed generated by a wind tower within the occupied zone of a specific residential building, the whole development has been considered and constructed in the empirical model testing.

According to National Housing Supply Council (NHSC), 2011 [24] there has been remarkable growth in the demand for apartment construction in Australian cities since the 1990s. The building design adopted in this study is typical of the medium-density, medium-height apartments being forecast to increase in many Australian cities by 2030 published in Climate Change Adaptation Research Facility (NCCARF), 2013 [2]. The model is a four storey development consisting of two separate apartments, each spanning two storeys. The living room, dining room, and kitchen areas are co-located on the first of the two floors, while the bedrooms are on the second floor. Modifications to the NCCARF reference apartment included, firstly, the orientation of the building to optimise the wind resource. Secondly, two wind towers (one for each of the two apartments in the building) facing the south façade of the building were mounted on top of the roof and connected to the living room spaces of each apartment (Figure 1).

2.3. Urban morphology and landscape design

Three different neighborhood urban morphology configurations have been developed around the apartment building scale-model. This paper is limited to the simplest of these, and reports the pressure difference analyses as well as the indoor air speed predictions generated by a wind tower attached to an isolated four storey apartment building embedded in a boundary layer terrain roughness category 2 (Figure 2a). Australian and NZ Standard 1170.2 [25] defines category 2 as "… *open terrain, grassland with few, well-scattered obstructions having heights generally from 1.5 m to 10 m*".

2.4. Empirical model set up

A model of a four storey apartment building was fabricated with transparent acrylic plastic (3 mm thickness) by printing in 3D stereo lithography at 1:100 scale. The model was sealed so that the surface pressure over the fenestration areas could be measured with pressure taps. Ninety nine pressure taps were installed over the five external façades of the scale model which was 19 cm in height, 17 cm in length, and 10 cm in width. Each pressure tap was connected to a manifold via an individual pressure tube that was connected, in turn, to a pressure transducer placed underneath the turntable (Figure 2b). In this study Reynolds number similitude for the scale model was relaxed since a) outdoor surface pressure measurements was of interest, and b), the model geometry was blocked [23].

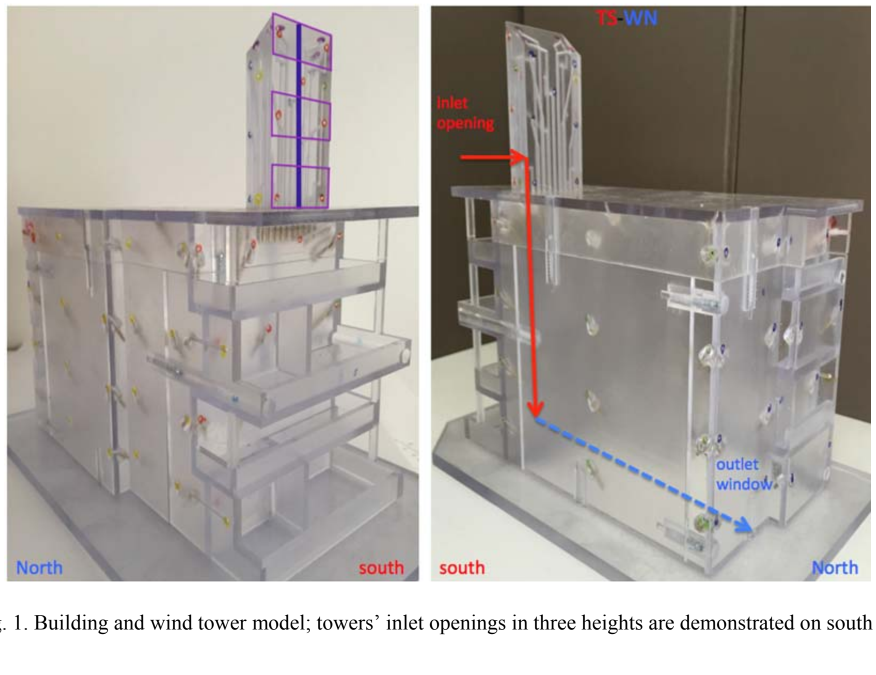

Fig. 1. Building and wind tower model; towers' inlet openings in three heights are demonstrated on south side.

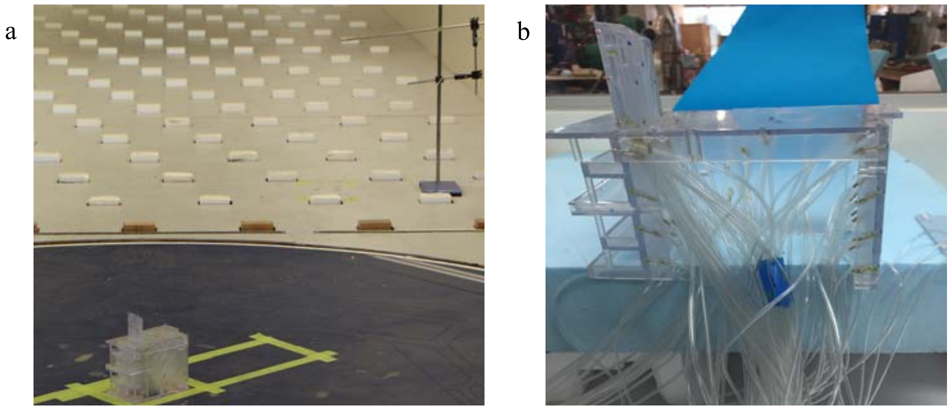

Fig. 2. (a) Pressure tapped model mounted on the turntable in boundary layer category two; (b) Model pressure taps and tubes.

2.5. Pressure and velocity instrumentations

The pressure tapped model was mounted on the turntable located on the wind tunnel test section (Figure 2a), where two manifolds have been connected to a pressure transducer which let the data acquisition system read the analog signals. Measured voltage of each tap was converted into a pressure reading according to the pressure transducer's calibration coefficient. A reference Pitot-static tube was located upstream of the model to measure the mean reference wind speed approaching the model at height of 0.5 m above the floor, which corresponds to 50 m at full-scale. The upstream dynamic and reference static pressures were continuously monitored with separate devices. Applying velocity profile for terrain category 2 in AS/NZS1170.2 [25], the pressure coefficient at the reference height could be rescaled to the building's height of 12 m. The experiments have been carried out for sixteen compass azimuth angles of wind direction, each for 100 seconds, which equates to about one hour at full-scale.

2.6 Results and discussion

2.6.1 Pressure measurements

Surface Pressure distribution over the openings of the wind tower on south side has been calculated against the pressure coefficient over the windows of the building on north and south facade.
For consistency with indoor air speed measurements, surface pressure measurements were converted into non-dimensional (n.d.) pressure coefficients relative to the upstream dynamic pressure at the building height (equation 1)[5,6,19,23]:

$$Cpe = (Pm - Ps)/(0.5\rho Ve^2) \quad (1)$$

where,
Cpe = mean surface pressure coefficient at building height (n.d.)
Pm = mean surface pressure (Pa)
Ps = mean static pressure at reference height (Pa)
ρ = density of air (kg/m^3)
Ve = mean wind speed at building height (m/s)

Figure 3 presents average pressure coefficients over the tower openings on the south side and the building windows on the north façade, for each of the sixteen wind directions. Average pressure coefficient over the tower south openings reaches 0.42, while the windows of the building on the north façade barely reached 0.2, around half of the towers openings' pressure coefficient. The maximum rate of tower openings yields 1.12, which is around 1.5 times the maximum pressure over the building windows at 0.77 at the north facade.

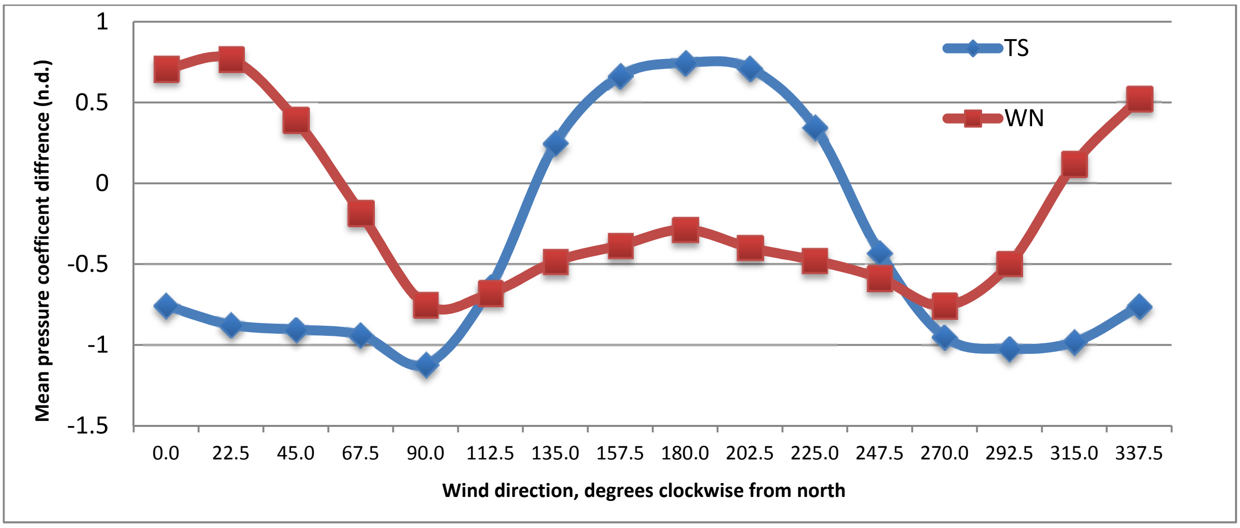

Fig. 3. Average pressure coefficient over the tower inlet openings on south side (TS) and building outlet windows on north facade (WN).

2.6.2 Pressure coefficient difference

The pressure coefficient difference between the wind tower openings and the building windows have been measured under sixteen azimuth angles of wind direction for two ventilation patterns: a) between the south opening of the wind-tower and the windows of the building on the north façade (Ts-Wn, the flow pattern is demonstrated in Figure 1(b)), and b) cross ventilation between windows on the south and north façades (CV in Figure 4). Results show that case (a) represents a considerable mean pressure coefficient differential of 0.85 with a maximum of 1.64 obtained during north - north east (NNE) winds, while the case (b) generates average of 0.68 and maximum of 1.2 of pressure coefficient difference under the same wind direction (NNE).

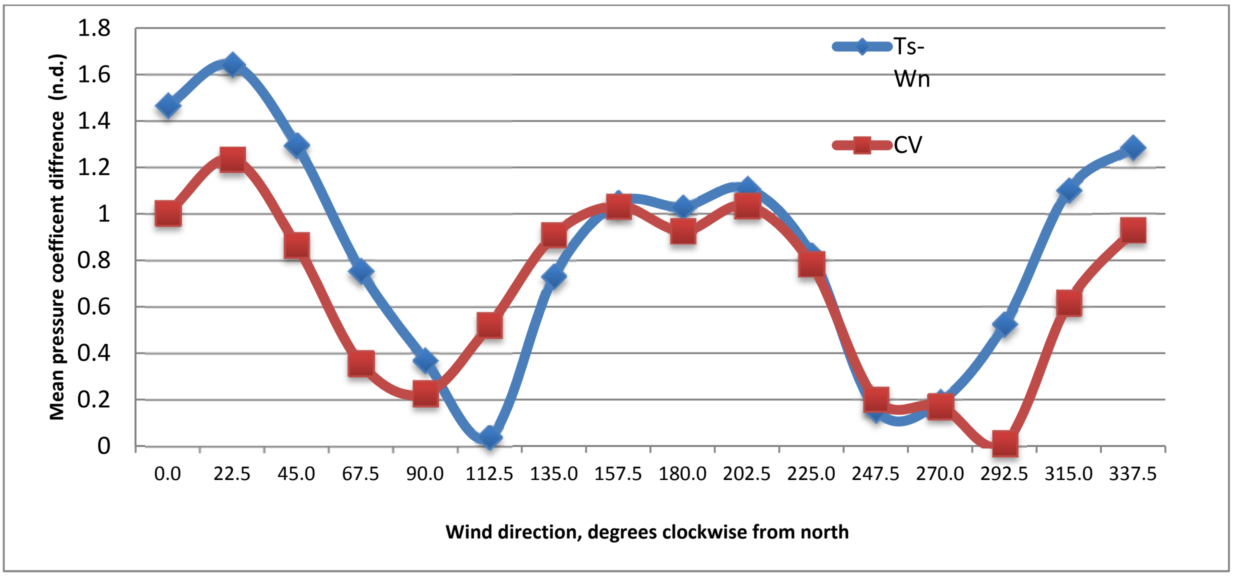

Fig. 4. Average pressure coefficient between tower openings in south and the buildings window in north (TS-WN) compared with the window cross ventilation (CV).

2.6.3 Indoor air speed calculations

To predict the air speed within the occupied zone, the relationship between pressure and velocity has been analysed through the dynamics of a particle of fluid; the complete analysis is very complex, however, since the flow in this study has been conceptualised as streamline flow, a number of simplifications have been applied based on Bernoulli's equation assuming that the flow is; a) steady i.e. not time dependent, b) inviscid i.e. viscosity forces are inconsequential, and c) irrotational [23]. Following Bernoulli's equation and the First Law of Thermodynamics on conservation of energy, a drop in pressure is accompanied by an increase in velocity, and *visa versa*. Therefore, the higher the pressure differential (ΔCp) over the building, the higher the velocity indoors. As to the consideration of energy loss in the system, the length, cross-sectional area, and perimeter of the conduit are the key factors, as they determine friction losses from the fluid as it moves through the duct. Additional friction within the duct, duct bends, duct exit and entry, all have the effect of reducing the airflow rate and they are lumped together under the term Total Energy Loss Coefficient (n.d.) in this study.

Entry loss and exit loss are assumed to be 0.5 (n.d.) in this study, bend loss is equal to 1.2 (n.d.), and friction loss was calculated according to the duct length (Ld), area (Ad), perimeter (P), surface roughness (k), and kinematic viscosity (*v*). The length of the duct depends on which floor of the apartment building is in question; therefore, for each floor a separate Total Energy Loss was calculated (Aynsley 1999). Following the thermodynamic laws, a series of equations were developed by the authors to transform pressure readings taken from the scale model building's exterior into the mean airspeed within the occupied zone of the full-scale building [27].

The indoor air speed calculations have been carried out based on the following constants:

- Room volume, L = 158 m^3
- Surface roughness, k = 3.00E-04 m
- Kinematic viscosity, ν = 1.50E-05 m^2/s
- Number of duct bends =1
- Wind tower opening area, Ao = 3 m2 (1.5m height * 2 m width)
- Cross-sectional area of duct, Ad = 3 m^2
- Perimeter of duct, P = 7 m (1.5 m * 2 m)
- Building Windows area, Aw = 1 m^2

A number of indoor air speed calculations have been conducted to optimise the wind tower design in an extensive parametric study examining the height, area and the sides of the tower openings. Erring on the conservative side, the tower with the lowest opening towards the south (centre point at 0.75 m above roofline), with the smallest cross-sectional area (3 m^2), and venting the lower level of the apartment building (i.e. with the longest duct) has been selected for the next phase of the analysis in which we apply wind-tunnel velocity coefficients to a climatological year of weather data.

3 Case study; Sydney Typical Meteorological Year 2013

This section analyses wind tower cooling performance in the humid-subtropical context of Sydney, Australia, by applying the findings from the wind tunnel experiments. A Typical Meteorological Year (TMY) file containing 8,760 hourly meteorological data sets corresponding to a climatologically average year. The 2013 TMY data file for Sydney developed by Boland in the NCCARF project [2, 26] has been adopted for this purpose.

3.1. Indoor air speed prediction in Sydney 2013

Figure 5 demonstrates the average indoor air speed via wind tower ventilation through a south-facing opening compared with through-window cross ventilation in the Sydney summer month of January 2013. Average outdoor wind speed in Sydney was 2.23 m/s at 10 m above ground, which has been up-scaled to building height at 12 m using the reference wind profile for terrain category 2 reported in AS/NZS1170.2 [25].

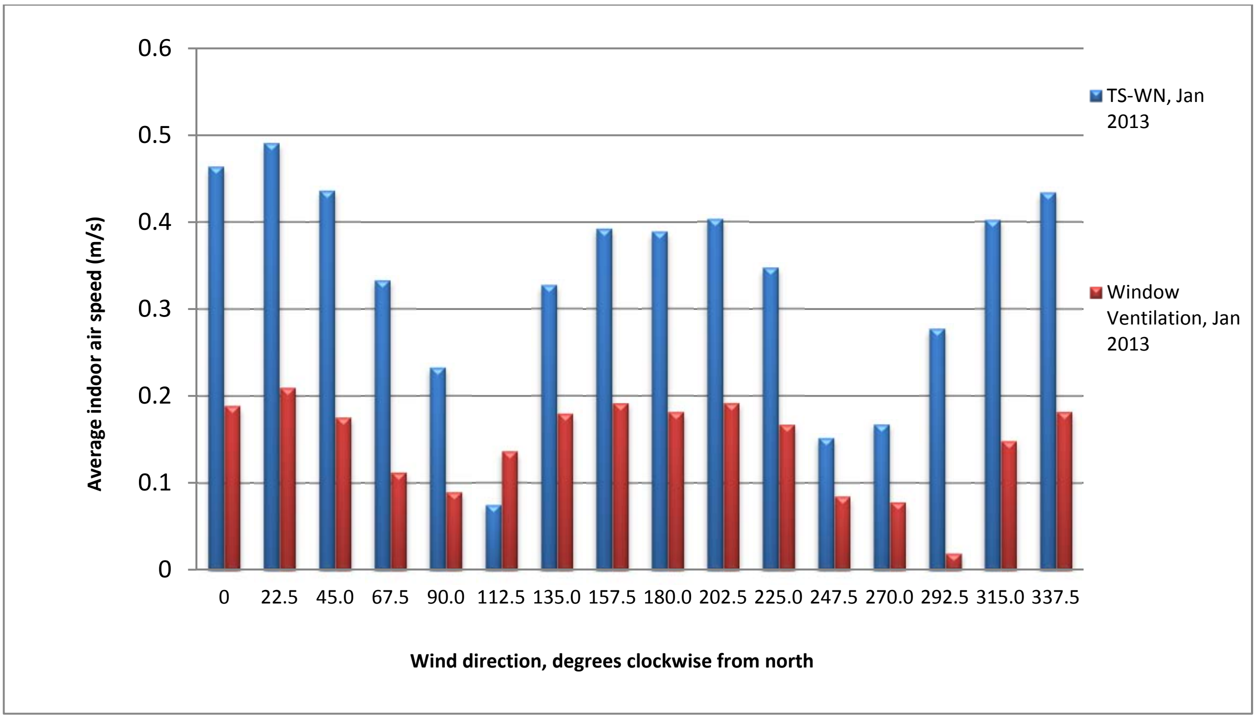

Fig. 5. Average indoor air speed (m/s) in January 2013 for wind tower with south opening (TS-WN) compared with window cross ventilation (CV).

Wind tower ventilation delivered an average hourly indoor air speed of 0.33 m/s, with the highest hourly average of 0.49 m/s recorded for the NNE wind direction (azimuth 22.5^o), which was more than twice the average speed recorded for through-window cross ventilation (average of 0.15 and maximum 0.21 m/s) during the same wind direction in January 2013. As depicted in Figure 6, the tower ventilation delivered on average 0.2 m/s higher air speed in the occupied zone than would have been the case for through-window cross ventilation under the South East wind direction (112.5^o).

3.2. Hourly indoor air speed simulations

To analyse the hourly cooling performance of the wind tower for the six warm/hot months in Sydney, the results of wind tunnel studies have been imported into the TMY via the following steps: First, non-dimensional velocity coefficient (Vc) was calculated based on the wind tunnel measurements, as a ratio between indoor air speed (Vi) and external reference velocity (Ve). Climatological indoor air speed was calculated from TMY using expression (2):

$$Vi = Vc \times Ve \quad (2)$$

Two sets of hourly indoor air speed (Vi) calculations were performed for the six warm/hot months of the year (October-March) using TMY 2013. Figure 6 compares the average Vi through a) wind tower with a south opening and exiting a window in the north façade (TS), and the default scenario b) through-window cross ventilation (CV). Wind tower ventilation achieved an average Vi of 0.43 m/s during the warm/hot months in Sydney 2013, compared to an average Vi through window ventilation speed of 0.17 m/s.

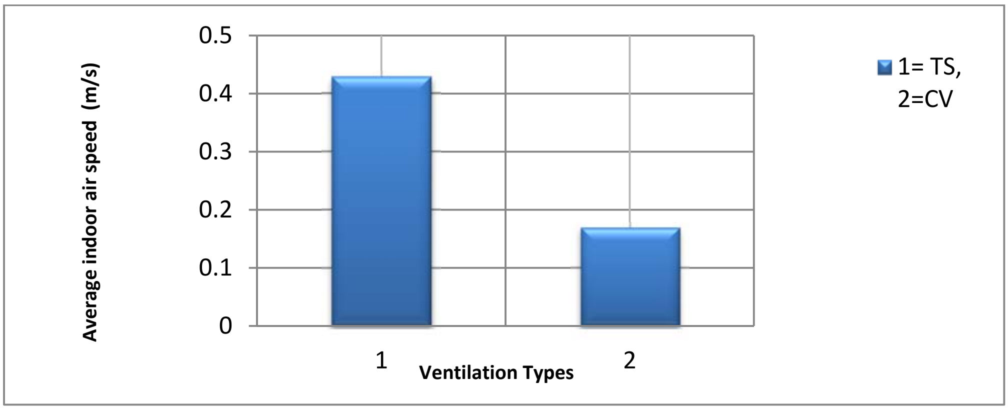

Fig. 6. Average indoor air speed (m/s) for tower ventilation with south openings (TS), and window cross ventilation (CV).

4 Thermal comfort analyses

ASHRAE Standard 55 [8] defines Thermal Comfort as that "… *condition of mind expressing satisfaction with the thermal environment*." According to existing literature, the envelope of acceptable indoor temperature can be stretched by elevating indoor air speeds [4-8]. To analyse the thermal comfort condition created by the wind tower, the Standard Effective Temperature (SET*) index has been applied to assess the impact of increased air speed in the occupied zone. SET* is the recommended model for assessing the comfort condition under elevated air speed above 0.2 m/s in ASHRAE Standard 55-2013 [8].

The results of hourly indoor air speed under the optimised design of wind tower in Sydney climate context, obtained from Section 2, have been applied in the SET* simulations using the ASHRAE Thermal Comfort Tool [28]. Air temperature and humidity were collected from the NCCARF 2013 report Typical Meteorological Year, while mean radiant temperature assumed to equal to air temperature. Metabolic rate and clothing insulation were set to 1 met (sedentary), and 0.5 clo (typical summer residential clothing) respectively. To compare the thermal comfort condition created by the wind tower, with the default window cross-ventilation, SET* simulations were performed hourly for both ventilation modes during the six warm/hot months in Sydney. Selecting just those TMY hours when increased airspeed was likely to be desirable, namely when air temperature was higher than the nominal neutrality of 23^{o}C (1,584 hours), SET* index values during wind tower ventilation were mostly lower than the default cross-ventilation scenario.

The difference between wind tower SET* and the through-window ventilation SET* (ΔSET*) has been termed the "Cooling Potential" of the wind tower. The cumulative total of ΔSET* across the six warm/hot months during hours when increased airspeed was likely to be desirable, has been calculated at 1725.8 SET* Degree Hours. This indicates the cooling potential of this conservative wind-tower configuration compared to the conventional through-window ventilation.

5 Conclusions

Wind tunnel experiments have been conducted to measure the surface pressure around a 1:100 scale model of a typical Australian apartment building. A series of equations were developed to transform the exterior pressure readings into mean airspeed within the occupied zone of the full-scale building. Indoor velocity calculations for several wind tower geometries and exterior designs (e.g. the orientation, area, and height of the openings), and in interior design (e.g. the duct configurations between inlet opening and outlet) have been conducted to optimise the wind tower design. Using the optimised design of wind tower, the model was exposed to the subtropical Sydney contemporary climate (TMY 2013) for the hourly indoor air speed calculations. In the next step, indoor thermal comfort analyses were preformed to calculate SET* to represent the cooling potential of the wind tower in comparison with the case of through-window cross ventilation. The key conclusions are as follows:

For wind-driven natural ventilation, the pressure differential between air inlet and outlet (fenestrations) is the driving force. The external design of the wind tower, building, and its neighbouring buildings all affect the wind-generated surface pressures. The height and the orientation of the inlet and outlet openings should be considered in the application of wind towers. In Sydney's TMY, the NNE wind direction produced the maximum pressure coefficient between the wind tower openings in south, and windows in the building's north façade, and this was consistently higher than the case of window cross ventilation.

The internal configuration of the tower (length of duct and number of bends) affects the total energy loss and consequently affects indoor air speeds. Air speed in the occupied zone was discovered to be particularly sensitive to cross sectional area of the duct. During Sydney's hottest summer month January 2013, a wind tower with south-facing opening and a cross sectional area of just 3 m^2 generated, on average, 0.2 m/s higher indoor air speeds compared with the through-window cross ventilation default scenario.

Thermal comfort analyses revealed that a wind tower with south-facing opening in the conservative configuration for this research project could reduce SET* by up to 6°C, and an average reduction of 1.1°C during the six warm/hot months of the year 2013, compared to the default scenario of through-window cross ventilation. Preliminary analysis with numerical modelling of the thermal performance of this apartment building in Sydney's climate indicate that the SET* reduction (ΔSET*) resulting from installation of a wind tower (termed the *comfort cooling potential*) is significantly greater than 1.1^{o}C once the effects of ventilation purging of heat stored in building thermal mass, leading to indoor mean radiant temperature reductions, have been take into account.

Acknowledgments

Financial support for this project was provided by the Faculty of Architecture, Design and Planning at the University of Sydney, and also the Centre for Infrastructure Engineering (CIE) at the Western University of Sydney. Also the authors extend their sincere gratitude to the CPP laboratory, Wind Engineering and Air Quality Consultants in Sydney for providing the wind tunnel experimental facilities. Dr Martin Belusko of The University of South Australia is also thanked for help with Typical Meteorological Year files.

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