Aerodynamic strategy applied in an urban shelter design

Simulation and analysis of aerodynamic phenomena in an urban context

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This paper presents an experimental study on strategies of utilizing wind as an architectural element, proposing the reconfiguration and projection of wind patterns to produce vaults of wind as regions of shelter in the outdoor environment. It shows an aerodynamic analysis and exploration of barriers, deflectors and porous screens in an existing urban wind canyon for a hypothetical urban shelter in a tram stop area. Computational Fluid Dynamics (CFD) software and physical tests in a wind tunnel using microelectronic hot-wire anemometry are the methods utilised. The experiments involve a comparison between screens with impermeable surfaces and porous membranes and their ability to project wind as architecture. The experiments showed that the use of porous membranes improves the mitigation level of wind speed and turbulence intensity in the wind vaults regions.

Keywords: *Urban aerodynamics, CFD simulation, wind discomfort, wind tunnel*

BACKGROUND

In many cases, urban configuration changes the pattern of wind flow, generating stream flows at the ground level and accelerating the wind; thus public spaces may require mitigation methods for local wind issues at the ground level (Stathopoulos, 2009). Even though, existing strategies to change or ameliorate pedestrian wind conditions near buildings are documented in the literature (Cochran, 2004), in some cases, the excessive use of canopies and trees difficult a normal incidence of sunlight or pollution dispersion in the outdoor environment. In general, it is necessary to elaborate new analysis considering local conditions of the urban configuration, wind speed, intensity and direction. For this reason, technologies for visualisation and wind analysis have become crucial to gain comprehensive knowledge of wind dynamics in an urban context to elaborate new strategies of design (Kim et al., 2011).

The field of numerical simulations (CFD) is under an intense process of change and improvement while wind tunnels are a reliable technology. In general, for architects there is a complementarity of both technologies in the professional field with their advantages and disadvantages (Salim and Castro, 2012). However, in the more specific area of the early design

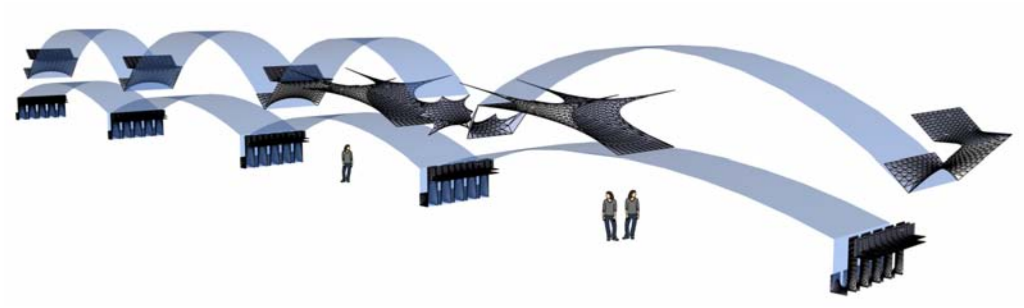

Figure 1
Sketch of protection bubble-regions. The arches represent the wind flow deflected

stage, CFD has become a useful tool for architects; especially, with new generations of CFD programs, such as Vasari, developed to be used by designers in the design process [1].

Moreover, porous membranes and permeable structures are being explored with new morphological approaches for designers to provide conditions of comfort. The current challenge is the adaptation and optimisation of these designs to be used in an urban context. In this sense, the studies of Jacques Gandemer about aerodynamic features of artificial windbreaks (Gandemer, 1979) provided a group of design rules to elaborate strategies of wind pattern manipulation that can be applied for the designer's explorations. These aerodynamic features might be fins, gaps, slots, or a graduation of porosity. A combination of these features can be strategically integrated into a flat porous screen. This can change the wind flow dynamics around the screen, increasing the protection area behind, while reducing the blockage factor of the wind mitigation feature. By reducing the geometrical domain of the element, opportunities arise in exploring wind as an architectural element.

RESEARCH AIM

The research aim is to analyse the differences in performance of impermeable surfaces and porous membranes to create architecture with wind and wind as architecture.

This research involves the analysis of windbreak aerodynamic features: fins as deflectors, porous screens, and slot systems. The approach is to use a passive strategy to manipulate wind patterns in an outdoor environment, to generate vaults of wind as protection regions for pedestrians (Figure1). This means the exploration is mainly about the wind aerodynamic patterns rather than to build complex screen designs. For the visualisation and analysis of the wind around the configuration of screens, experiments with CFD simulations and a physical wind tunnel were performed. In the case of the wind tunnel experiments, the goal was to verify the architecture of the wind projected by porous membranes that are too complex to analyse using Vasari.

EXPERIMENTAL METHOD

The context

Because of the complexity of the conditions involved with aerodynamic urban phenomena and the limitation of wind measurement instruments, it is necessary to simplify the simulation and to use standard conditions as parameters for this analysis. Thus, typical wind phenomena and context are used as the case for this research: an aerodynamic phenomenon called Channel Effect (Gandemer et al., 1978) which produces pedestrian discomfort due to high wind speed along a narrow street (Erell, Pearlmutter, et al. 2011). This kind of phenomena is very common in the city and can be viewed as a representation of the case observed in a tram stop area in the business district of Melbourne, Australia. For instance, figure 2 shows the wind measurement in this typical tram stop area in Swanston Street in the CBD of Melbourne (Figure 2). The wind fluctuation in this place is over 5 m/s, which is considered as beyond the discomfort threshold for wind speed in this context (Figure 3).

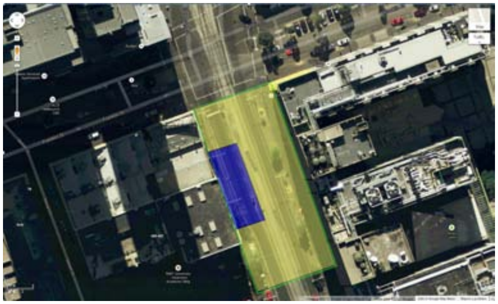

Figure 2
Tram-stop area in the business district of Melbourne

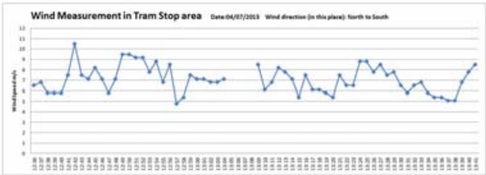

Figure 3
Fluctuation of wind speed in the tram stops area (weather station data)

Thus, because of the street configuration, which produces this kind of phenomenon, the area analysed must be defined considering this two spaces: the street space and a tram stop site. Swanston Street is orientated from South to North and has 30m width including a tram track of the Public transport system. The area is surrounded by tall buildings that shape a closed channel. In this street a tram stop was built near the intersection between Swanston St. and Franklin St. The tram stop has an area of 4.5m width and 69m length on the west sidewalk of the street. The site has urban furniture and shelter of two glass roofs to protect pedestrians. The problem of discomfort is produced due to strong wind speeds running from the north to the south, along the street and near the corners.

The localised wind phenomena are difficult to attribute to the influence of tall buildings surrounding the site. But some statistics show a trend of prevalent winds from North to South during the second half of the year (Bureau of M, 2013)[2]. This is coincident with the personal experience of the authors: recognition that this problem is more frequent in the winter season. Here, there is no protection from natural foliage of trees and the wind flows at ground level with high velocity.

The tram stop configuration

The installations are physical aerodynamic features based on windbreak designs to generate wind thresholds. This can be understood as upward deflections of the wind that produce a chain of bubbles of low wind speed (protection regions). Therefore, the wind mitigation elements must create a layer of low pressure above the tram stop area. These elements are gathered in five groups along the tram stop, including a structure of the roof for the shelter. With the association of three essential elements: a porous screen with 20% porosity, a horizontal curved fin as a deflector with a double slot system and a convex deflector above the barrier, the main requirement is to keep a low porous barrier (1.5m height). The area of protection is associated with the wind deflection (wind vault) created by the porous barrier.

The tram stop configuration has five parts, four vertical deflector components and a roof (Figure 4). These elements are organised strategically to define four regions within the tram stop area.

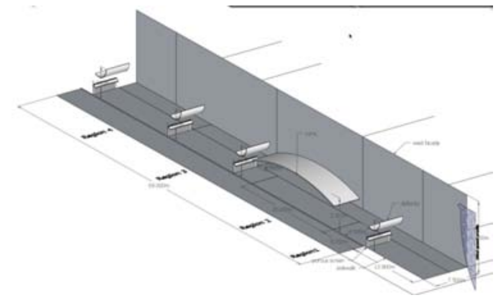

Figure 4
Configuration of the tram-stop with screens and roof

Above each screen, there is a curved surface of 2m height. This surface is a deflector that creates a wake region and low pressure layer at the top of the protection area. The idea is to produce a vertical lift effect of deflected wind to increase the height of this region. The total height of this screen is 5m (Figure 5).

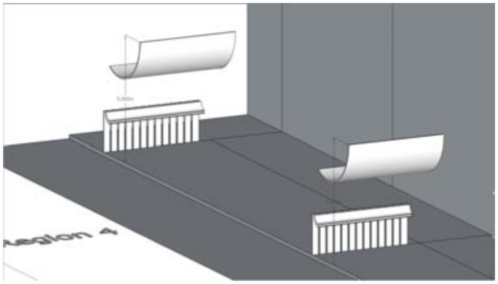

Figure 5
Porous screen of 20% of density. Horizontal deflectors with double slot as accelerator. Convex deflector above of the barrier

EXPERIMENTAL PROCEDURE PART 1
Numerical simulation using CFD software

The initial design concept was evaluated using CFD to verify the most relevant phenomena and introduce modifications for further tests. The use of the engineering CFD software can be difficult for architects because it requires expertise in numerical analysis and knowledge in wind engineering. Alternative easy-to-use programs, such as Vasari, can be used, but they have limitations in wind parameters such as the simulation of the atmospheric boundary layer (ABL) effect. This parameter can produce strong changes in the CFD analysis outcomes. The software used in these simulations was ANSYS to take advantage of its extended capabilities to represent wind phenomena in an urban context i.e. ABL simulation. But the complexity of the context and aerodynamic phenomena can be an additional challenge for an architect to realise this kind of simulation. Thus, simplification and standardisation of many factors facilitates the simulations and the feedback with these initial experiments. For the numerical simulation, the urban context was represented as a simple and regular geometry of a channel. This geometry is a fluid domain where the channel effect was recreated as a digital mesh. This volume was 30m wide (similar to the distance between opposite facades), 16m high and 69m long. Four faces of the geometry represent the ground, sky and street facades, while two end faces represent the fluid inlet and outlet zones. A low grade of roughness is given to these surfaces to simulate the friction of facades and ground.

The wind profile at the inlet was setup as flow with a boundary layer effect, considering the power boundary layer equation and using a reference velocity relevant to the discomfort threshold - a speed of 5m/s at 1.5m height (Wisse, 1988). Also, in this case, wind flows only in one direction and the corner wind effect is omitted. The turbulence intensity was assumed to be 5%, and other objects were not considered in the area of the tram stop. Inside the Fluid Domain, a refined digital mesh is built achieving a more accurate solution of the wind phenomena such as the wake regions, the chain of aerodynamic bubbles and the level of wind deflection around the tram-stop. This refined domain has 10m high, 15m wide and 46m in length.

CFD Simulation Results

The engineering CFD simulation of these aerodynamic features showed several strong upward deflections (wind vaults) and protection regions behind each porous barrier, and along the area of the tram stop. This analysis and clear visualisation informs the designer of the patterns of wind flows for further experiments in the physical wind tunnel. One of the findings is that the aerodynamic bubble produced at the leeward side of the screen is higher than a similar screen without deflectors. This effect is coincident with the findings of Gandemer's studies, where he mentioned the use of fins integrated with the barriers as a method to increase the protection area behind a screen (Gandemer, 1979). The initial CFD simulation results confirmed the design concept of fins and slots at the top to produce a effect of vertical deflection. based on the initial finding, a new design strategy with an additional deflector above the screen is formulated. The effect of vertical deflection is more significant with this deflector and another of the effects observed is the regular form of the bubbles in the last three vertical screens. These screens installed in parallel define a more regular and continuous protection area (Figure 6). In fact, the first vertical screen after the group of roofs helps to reorder the wind flow that passes through the shelter zone and increase the protection region behind the group of roofs.

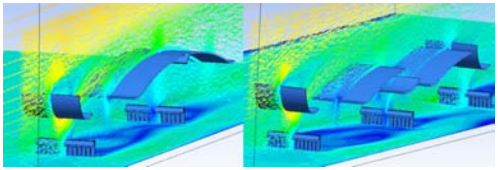

Figure 6
Areas of wind deceleration under the curved roof

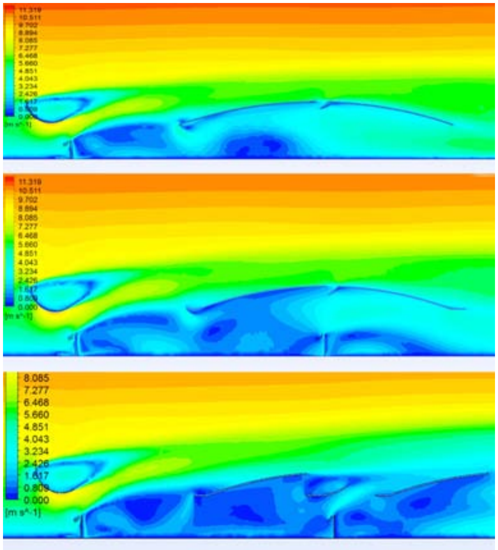

Figure 7
Variation of the wind flow below the roofs

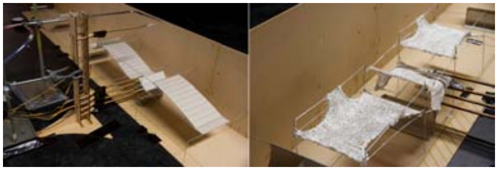

Figure 8
Model scale for the wind tunnel. Left: opaque surface. Right: porous membrane

The most interesting observation of this visualisation was the fact that a roof with continuous surface produces an acceleration of wind speed in the region below. In contrast, if the roof is split in three parts with gaps, the wind speed is lower below these roofs (Figure 7). Based on the engineering CFD simulation results, for the experiments in the wind tunnel, the configuration of the roof was changed to three roofs.

EXPERIMENTAL PROCEDURE PART 2
Physical simulation using a wind tunnel

After the CFD simulations, physical tests were conducted in an atmospheric boundary layer condition within a wind tunnel simulating wind around the screens and deflectors. The scale models (1:30) of the screens with modifications were installed along a panel representing the footpath and west face of the street. The second group of experiments were conducted, changing the roofs composed of surfaces with porous membranes to analyse their performance as deflectors and wind mitigation devices (Figure 8).

The use of a wind tunnel can be a complicated task, but the main problem is the difficulty of obtaining accurate and rapid feedback of the simulation outcomes. To facilitate the visualisation and comprehension of the phenomena observed in these experiments several micro wind sensors were installed, after a process of calibration, to collect and visualise quantitative data in real time. In addition, a graphic interface was composed to read the data from the sensors. This platform was developed using a system of low-cost components, including micro wind sensors, an Arduino board, Grasshopper, Firefly and Rhino3D. To know more technical details about this sensor platform, see the work "wind sensing with real-time visualisations for designers" (Prohasky, 2014).

The aim of these physical experiments was to verify (with simple geometries and porous meshes) the level of vertical deflection of the wind behind the first screen configuration and to measure the wind speed above the area of roofs. Thus, the tests were separated into two stages: the first group of experiments with simple geometries of surfaces and a second group of experiments with porous membranes.

The condition in the wind tunnel considered a wind velocity profile of atmospheric boundary layer at 1:30. Reference velocity at 50mm measured by petot static tube (3.95m/s). The equivalent reference velocity at 1:1 scale is located at an elevation of 1.5m. The boundary layer was estimated based on the power law equation (Aynsley, Melbourne, et al. 1977) (Figure 9).

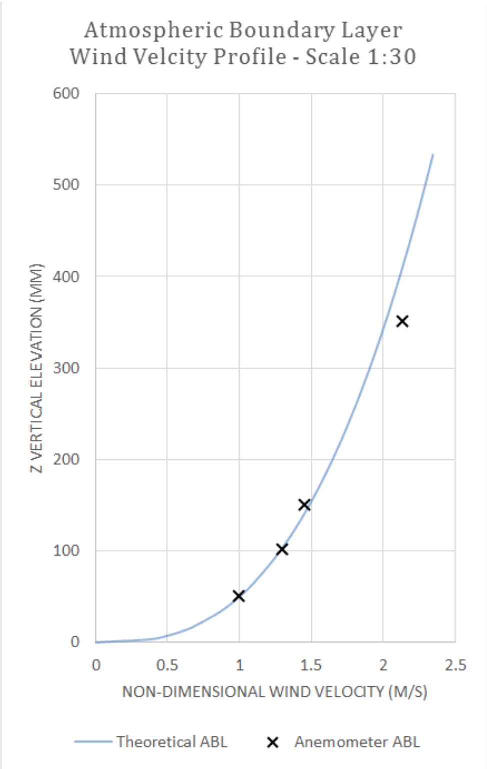

Figure 9
Wind velocity profile of atmospheric boundary layer condition at 1:30.

Experiment with a vertical screen

The first region tested with the group of micro wind sensors in the ABL wind tunnel experiment was behind the first porous screen and deflector canopy. In this place, the sensors measured the velocity intensity at 50mm, 75mm, 100mm, 125mm, eight (scale model 1:30 / 50mm=1.5m). To have a clear idea of the changes in the wind flow pattern three tests were conducted: no screen and deflector, first screen and deflector (simple geometries), first screen and deflector (porous meshes), and a fourth - no screen and deflector (second post reference).

The results show that the velocity profiles behind both screens are quite similar. Only the sensor at 125mm height detected lower velocity in the wake region behind the porous canopy than the impermeable surface canopy. But this difference does not change the velocity at the other levels (Figure 10). Therefore, this shows that the vertical upward deflection of wind produced by the screen, it is not affected if the canopy is a porous membrane.

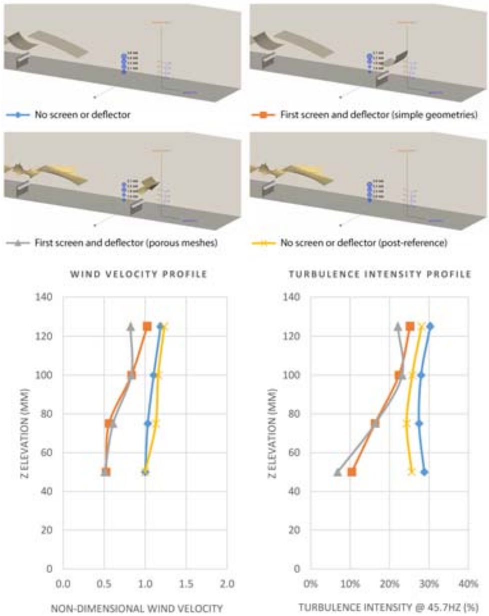

Figure 10
Positions of sensors for four tests and results of the four tests with a vertical screen (porous and opaque surface)

Experiment with a lateral deflector

A second experiment involves the evaluation of the first screen configuration and the effect produced by a lateral deflector with a shorter screen. Two experiments were set up to compare the effect: a first ex-

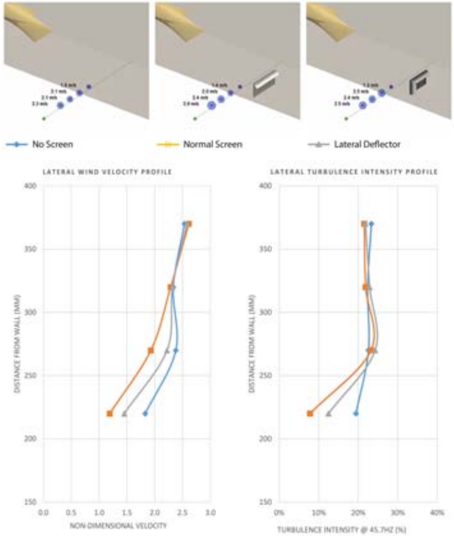

Figure 11
Three tests for a lateral deflector and results

periment of a lateral deflection of the wind in a standard screen and a second test with a shorter screen with a lateral fin. The distances are taken from the vertical wall of the model. The results showed that the lateral deflector extended the boundary of the protection region. A smaller screen with the lateral deflector provided very similar conditions of wind mitigation in the whole area of the sensors (Figure 11).

Analysis shelter area

Two sensors were placed in three positions below the roofs in the shelter area, for the last group of experiments. They were installed to measure the wind speed at head level to capture the effects of wind relevant to pedestrians and the effects of split roofs and roofs made with porous meshes.

The results of these experiments showed that the level of wind velocity in the area of the shelter (pos 2, 3) decreased using porous membranes. Besides, in the position 3, the turbulence intensity is lower below the membranes, but it did not change at the head level (Figure 12).

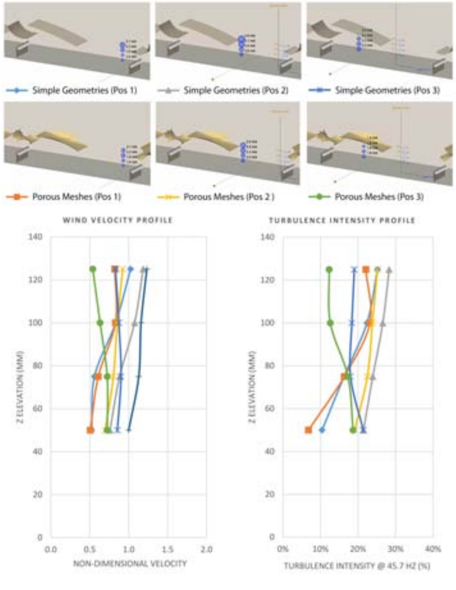

Figure 12
Six tests for opaque and porous surfaces in the shelter area and results

Results wind tunnel

The graphs generated were standardised into non-dimensional wind velocities relative to the reference velocities at relative pedestrian level measured from ABL conditions. Two reference wind velocity profiles were used to account for reference wind velocity drift during the experiments. The turbulence intensity plots are provided in addition to the average wind velocity since the data was available to do so. In subsequent papers, the wind sensors will be analysed for their responsiveness and reliability in measuring turbulence intensities. Though, the nature of the results seem quite satisfactory after deconstructing the evidence. In general, the wind velocities are reduced further with the porous deflectors with respect to the solid deflectors. And turbulence intensities are also decreased in the same fashion due to the graduated distribution of pressure differences by filtration through the porous elements.

CONCLUSION

The aerodynamic phenomena around buildings and wind issues in pedestrian areas are an opportunity for experimentation with new mitigation strategies involving explorations of wind dynamics and digital and physical technologies of simulation and visualisation (CFD and wind tunnel). Consequently, the visualisation and analysis of screen configurations using CFD allow us to plan a better strategy of analysis in the physical wind tunnel. This strategy was focused on specific regions and effects of wind to evaluate their behaviour, but at the same time, the questions generated from two methods of simulation (empirical testing with digital sensing and CFD) were verified through comparison across these two technologies.

OUTLOOK

The parallel use of numerical simulation and physical simulation produces a complementary approach to improve comprehension of complex wind phenomena. For instance, to design the experiments in a wind tunnel required a general prediction of results. The position of the sensors must consider the most significant points to measure reliable data to derive relevant conclusions. In this sense, the visualisation provided by the CFD software can be useful to define the areas to test in physical experiments. Thus, both technologies provide not only data, but rather, support the facilitation of the design process in the discoveries and manifestation of the architecture of wind.

REFERENCES

Aynsley, R.M., Melbourne, W.H. and Vickery, B.J. 1977, *Architectural aerodynamics*, Applied Science Publishers, London

Cochran, L 2004 'Design Features to Change and/or Ameliorate Pedestrian Wind Conditions.', *Structures Congress 2004 American Society of Civil Engineers.*, Nashville, Tennessee, United States

Evyatar, E, Pearlmutter, D and Williamson, T 2011, *Urban Microclimate. Designing the Spaces between Buildings*, Earthscan from Routledge.

Gandemer, J 1979, 'Wind Shelters', *Journal of Industrial Aerodynamics*, 4, pp. 371-389

Gandemer, J 1978, *Discomfort due to wind near buildings: aerodynamic concepts*, Dept. of Commerce, National Bureau of Standards, Washington, D.C., U.S.

Kim, J, Kyu Yi, Y and Malkawi, AM 2011 'Building form optimization in early design stage to reduce adverse wind condition, using Computational Fluid Dynamics', *12th Conference of International Building Performance Simulation Association*, Sydney, Australia

Prohasky, D, Moya Castro, R, Watkins, S, Burry, J and Burry, M 2014 'Wind sensing with real-time visualisations for designers', *Proceedings of eCAADe 2014*, Newcastle upon Tyne

Salim, F and Moya Castro, R 2012 'Parallel Analysis of Urban Aerodynamic Phenomena Using High and Low-tech tools.', *Proceedings of eCAADe 2012*, Prague, Czech Republic, pp. 621-629

Stathopoulos, T 2009 'Wind and Comfort', *EACWE 5*, Florence, Italy

Wisse, JA 1988, 'A Philosophy for Teaching Wind in the Built Environment', *Energy and Buildings*, 11, pp. 157-161

[1] http://www.academia.edu/4820747/Evaluation_-of_simulation_tools_for_assessment_of_urban_form_-based_on_physical_performance

[2] http://www.bom.gov.au/climate/averages/tables/cw_-086071_All.shtml