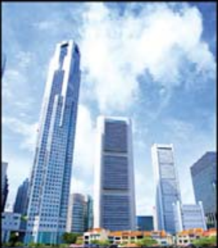
URBAN AERODYNAMICS

Wind Engineering for Urban Planners and Designers



Task Committee on
Urban Aerodynamics

ASCE

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Wind Engineering for Urban Planners and Designers

PREPARED BY
The Task Committee on Urban Aerodynamics
of the Technical Council on Wind Engineering
of the American Society of Civil Engineers

ASCE

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Task Committee on Urban Aerodynamics

The Task Committee on Urban Aerodynamics was formed under the auspices of the Aerodynamics Committee of the Aerospace Division of ASCE. The Technical Council of Wind Engineering (TCWE) was created in 2007 and the activities of Aerodynamics Committee were transferred to the Environmental Wind Engineering Committee of TCWE. Several members of the Task Committee on Urban Aerodynamics, under the leadership of Richard Aynsley, were committed to complete the work of this SOA report on Urban Aerodynamics. The final product, which was peer reviewed, was approved by the ExCom of TCWE (Theodore Stathopoulos, Chair, Bogusz Bienkiewicz, Leighton Cochran, Peter Irwin, Ahsan Kareem) in February 2011.

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CHAPTER 5

CHAPTER 1

INTRODUCTION

The ASCE Aerodynamics Committee was formed in 1976. Decades before this relaxation of urban development regulations resulted in an increase in construction of high-rise buildings around the world. There have been a variety of reasons for limiting heights of buildings in urban centers. Building heights in Sydney, Australia were limited to 150ft (46m), the height of the available fire rescue ladders until 1950. Similarly building heights in London, UK, were limited to 30m to ensure fire rescue by ladder from the highest floors. In Japan building heights were limited to 31m until 1963 when *floor area to plot ratio* regulations were introduced for tall buildings. Until 1973, buildings in downtown Ottawa, Canada were limited to 149 ft (45.5m) so that the Peace Tower on the Parliament buildings would remain prominent on the skyline.

Designing these taller buildings presented problems with respect to the simplistic wind load codes of the time. Boundary layer wind tunnels were developed to provide more detailed information on total wind loads, cladding loads, and safety of wind conditions at pedestrian level around buildings. Most wind tunnel studies related to a single building or structure, but some studies considered broader regions with respect to airborne pollution or relative wind speeds over complex topography.

In the past, before the emergence of wind engineering, wind was often a consideration in urban design, particularly when choosing a site for a new city. Designing new cities has been a relatively rare activity in recent decades. However, with rapid urbanization generated by increasing affluence, a number of new cities have been designed in China and Malaysia in recent years (Table1).

In the USA existing urban centers have been expanding. This activity can benefit from wind engineering, although many urban planners and designers often do not seek out professional wind engineering advice. This booklet prepared by the ASCE Task Committee on Urban Aerodynamics provides an overview of wind engineering and serves as a means to introduce the quantitative methods wind engineering has to offer to urban planners and designers who have tended to rely on an intuitive approach.

Urban planners are expecting that both city populations and the percentage of people living in cities will increase (Acioly and Davidson 1996; Bruegmann 2005). Predictions are that, between 1990 and 2025, the number of people living in urban areas will double to more than 5 billion; if that occurs, then almost two-thirds of the world's population will be living in cities. Interestingly, 90 percent of that increase will occur in developing countries (WRP 1996).

The world's urban population is currently growing at four times the rate of the rural population (Central Intelligence Agency 2009). There is likely to be national and global population drift from cold to warm climate regions as winter heating energy costs escalate. In warm humid regions urban environments need adequate flow of air to offset outdoor heat stress and better planning and construction to mitigate wind damage from hurricanes.

OBJECTIVES OF THIS BOOKLET

The objectives of the Task Committee on Urban Aerodynamics were:

I. To identify professional contributions that wind engineers can make to urban planning and design.
II. To assemble information into a booklet for publication by ASCE, promoting these quantitative professional contributions that wind engineers can make in urban aerodynamics in collaboration with city governments, urban planners, and designers.
III. To prepare a selected bibliography on wind engineering in urban aerodynamics as a guide for further reading.

SCOPE

City planners and urban designers need to be aware of tools and quantitative techniques used by wind engineers in urban aerodynamics and how they can benefit from adopting quantitative techniques in lieu of an intuitive approach. This document introduces basic tools and technology used in the study of urban aerodynamics and highlights the many advantages wind engineering can offer when integrated into the design/development process. This document does not treat the use of wind tunnel testing to quantify load effects on structures through pressure or force measurements. This is treated by a separate ASCE manual of practice: *Wind Tunnel Studies of Buildings and Structures* (ASCE 2005) and by the ASCE Technical Council on Wind Engineering (TCWE).

Elements of Urban Aerodynamics

Elements of urban aerodynamics include an understanding of the general global circulation within Earth's atmosphere and the resulting characteristics of wind as they vary with latitude. These winds have differing effects on urban populations in colder latitudes than populations in warmer latitudes, nearer to the equator.

Urban planning and urban design considerations of wind are evident in early civilizations (see Chapter 2). Some recorded examples include street orientation to enhance summer breeze penetration while providing shelter from chilling winter winds. Other examples are the choice of sites for new colonial cities to facilitate efficient navigation of sailing ships. These early intuitive examples were based on general observations of wind effects. More contemporary consideration of urban aerodynamics includes development of quantitative approaches to wind engineering based on long term statistical wind data.

Wind Engineering in Urban Aerodynamics

Contemporary examples of wind engineering in urban aerodynamics reflect earlier considerations of street orientation to enhance summer breeze penetration while providing shelter from chilling winter winds. These have benefited from the development of quantitative models of human body heat exchange and response to thermal environments.

Other examples of contemporary urban aerodynamics extend considerations to include quantitative studies of dispersion of airborne pollutants over urban environments, mitigation of high speed wind gusts at pedestrian level near tall buildings (Isyumov et al. 1976). Mitigation of wind damage applies to both tornadoes in higher latitudes and hurricanes in lower latitudes. Most recent developments tend to focus on two considerations: potential for local urban energy from wind turbines, and studies to predict likely airborne distribution of toxic materials from biological or nuclear weapons detonated in or near urban areas.

Tools and Techniques

Boundary-layer wind tunnels are a principal tool of wind engineers in urban planning and design projects. The use of small-scale models, in a boundary-layer wind tunnel has become routine in the study of the effects of terrain and complex cityscapes on airflow at ground level and at elevation in downtown areas for both high-speed pedestrian winds and for the removal of stale or polluted air (Sun 1989; Cochran and Howell 1990). Boundary layer wind tunnel studies using tracer gas techniques are frequently used by wind engineers to assess the probability of acceptable concentrations of vehicle exhaust emissions or even chemical agents. Similar studies have been used to determine the optimum location of fresh air intake openings for building ventilation systems. Likewise, prediction of smoke cloud concentrations by wind engineers in urban spaces resulting from building fires can assist in avoiding smoke entry into fresh air intakes.

Computational fluid dynamics (CFD) solves simultaneous Navier-Stokes partial differential equations at many millions of grid points in a flow field. This technique became practical for large scale flow with the development of super computers. Early CFD pioneers in the field of urban aerodynamics (Murakami 1993) found that the classic turbulence models frequently used in CFD software were not suited to modeling large scale flows around bluff body shapes common in building shapes. More recently, the rapid increase in computing speed of smaller computers has made CFD accessible to a much wider range of people interested in urban aerodynamics. The most critical step in any CFD modeling is to calibrate the settings chosen for the modeling by comparing results of CFD computation with some physical measurements to validate the CFD output.

Field studies are used in urban aerodynamics to collect data for direct use in design or to use in calibrating fluid dynamics CFD models (Aynsley and Su 2003). Use of field studies is often constrained by cost, time, and instrumentation.

Selected Bibliography

An important part of the Task Committee's work is the preparation of a selected bibliography on wind engineering in urban planning and design. There are no established text books on the subject of urban aerodynamics, as was the case in wind engineering generally in the 1960s. Many of the most relevant publications on the subject are in conference proceedings or journals. The selected bibliography included in this booklet will provide a useful guide for further reading for people unfamiliar with the subject.

Table 1. Global Urbanization Trends (Central Intelligence Agency 2009).

Country	Urban Population % of Population 2008	Urbanization Rate % (2005-10 estimate)
Hong Kong	100	1
Indonesia	52	3.3
Malaysia	70	3
Laos	31	5.6
Vietnam	28	3.1
China	43	2.7
India	29	2.4
United States	82	1.3
United Kingdom	90	0.5
Germany	74	0.1
Australia	89	1.2
Venezuela	93	2
Brazil	86	1.8

CHAPTER 2

ELEMENTS OF URBAN AERODYNAMICS

HISTORIC CONSIDERATION OF WIND IN URBAN PLANNING

There is extensive evidence that previous civilizations gave serious consideration to the impact of prevailing winds on urban settlements (Aynsley et al. 1977). Egyptians planned the town of Kahan in 2000 B.C. (Figure 1), so that houses for workers on the western perimeter shielded the houses for officials in the north from hot desert winds. The housing for officials gained full benefit of pleasant winds from the north.

Vitruvius, a Roman architect and engineer in the first century B.C., wrote in his highly influential *Ten Books on Architecture* (Vitruvius 1960) how Roman garrison towns were planned with a rectangular grid pattern of streets obliquely aligned to the harsh winter winds to reduce the chilling effects of winter winds. This arrangement was said to protect entrances and courtyards.

"*Then let the directions of your streets and alleys be laid down on the lines of division between the quarters of two winds.*

On this principle of arrangements the disagreeable force of the winds will be shut out from dwellings and lines of houses. For if the streets run full in the face of the winds their constant blasts rushing in from the open country, and then confined by narrow alleys, will sweep through them with great violence."

"*By shutting out the winds from our dwellings, therefore, we shall not only make the place healthful for people who are well, but also in the case of diseases due perhaps to unfavourable situations elsewhere, the patient, who in other healthy places might be cured by a different form of treatment, will here be more quickly cured by the mildness that comes from the shutting out of the winds.*" (Vitruvius 1960, pp.25, 27)

These design features were later adopted in the 15th century by the Italian Leon Battista Alberti who was responsible for their dissemination through France, Germany and Spain as well as Russia. Town planning laws established by the Spanish for their new colonial towns in the Americas in the 1500's included consideration of local prevailing winds. These laws required that sites be sheltered from undesirable winds and avoid open water to the south and west that would hinder the approach of sailing ships with channels leading into the wind. Around 1745, streets in Buenos Aires were carefully oriented in the city plan to prevent prevailing winds from sweeping through the city (Figure 2).

The Indian city of Hydrabad, with its narrow streets and alleys, is characterized by numerous tall wind scoops rising from the roofs of buildings for natural ventilation (Figure 3). These scoops direct prevailing winds down into the buildings through the principal rooms and out into the street.

INFLUENCE OF INDUSTRIAL REVOLUTION ON TOWN PLANNING

In 1874, the new towns in Sweden built to house workers to meet the needs of industrial growth, led to the introduction of planning ordinances to ensure adequate daylight and natural ventilation to maintain health of occupants. Urban planners in Vienna around 1900 considered prevailing winds in land-use zoning to avoid smoke from factories being blown across built-up areas (Aynsley et al. 1977). Similarly the English garden cities of Letchworth see Figure 4, and Welwyn have the industrial quarter on the east side of the town so the prevailing wind blows the smoke from factories away from town. In Russia, the urban planner Muljutin took similar precautions when he planned the city of Magnetogorsk.

New dormitory towns in New Jersey for people who commute to work in New York City were planned with shelter belt vegetation. The shelter belts shield the town from undesirable winter winds from the northwest while encouraging pleasant summer breezes from the southwest (Olgyay 1992, Figure 5).

CONTEMPORARY CONSIDERATION OF WIND IN URBAN ENVIRONMENTS

In the 1960s, improved fire safety was gained from the installation of automatic sprinkler systems in tall buildings. This, combined with the relaxation of building height restrictions, led to a wave of tall office building development. Earlier height restrictions of around 150 feet were set by limitations of fire fighting and rescue ladders. Wind engineering as we know it today developed with the rapid increase of tall building construction during this period.

Pedestrian Level Winds

Increases in gust wind speeds at street level around the base of tall buildings led many cities to introduce regulations aimed at controlling winds at street level. Typically the regulations called for a report predicting probable street level wind speeds based on a wind tunnel study when proposed buildings exceeded a specified height.

These were the early days in the study of wind around buildings, and people came to associate undesirable street level wind effects around the base of these new tall buildings (Figure 6) with their height. Building height was only an indirect factor. The building shape, location and height relative to nearby buildings were the main factors that influenced street level wind environments. All these factors determined during the very early stages of development proposals were often decided by people that had no specific knowledge or training in the then embryonic field of wind engineering. Many uninformed architects and developers saw the new regulations relating to street level wind as unnecessary bureaucratic obstructions to their projects. Over the past twenty years significant advances have been made in the science of wind engineering. International research collaboration has resulted in broad agreement on acceptable pedestrian or street level wind criteria (Lawson 1973; Isyumov and Davenport 1975).

The American Society of Civil Engineers (ASCE 1999) has published recommended procedures for conducting wind tunnel studies of buildings and their surroundings to ensure consistency between results from different wind tunnels.

Standard procedures have been developed for determining the probability of street level wind gusts from wind tunnel data together with long term weather records. These are discussed in detail in the companion ASCE booklet titled *Outdoor Human Comfort and Its Assessment* (ASCE 2003).

City governments have responsibility for the safety and convenience of people using urban public space in the forms of sidewalks, roadways, parks and other public open space under their authority. Combining this responsibility with a growing awareness of the public and the legal fraternity of a causal relationship between buildings and street level winds, results in an increasing risk of litigation in the event of wind related accidents.

There are a number of cases around the world of wind accidents in which people sustained serious injury or were killed. In May of 1972 in Portsmouth, England, an elderly lady died after her skull was fractured in a fall caused by a gust of wind at the corner of a 16 storey building. In June of the same year in Birmingham, England, another elderly woman was lifted off her feet by a gust of wind near a tall block of apartments and died of head injuries as a result of her fall (Aynsley 1986). In December of 1982 in Canada, a family of four was seriously injured when they were blown off a jogging track on the podium roof of the Toronto City Hall (The Globe & Mail 1983).

Within the United States, in 1982 a woman was blown to the ground by a gust of wind seriously injuring her shoulder near one of New York's tallest buildings (Aynsley 1986). She later sued the building's owners, manager, design engineer, architect as well as New York City for $6.5 million. The woman's attorneys claimed that the defendants in the case were negligent in allowing a building to be built that created dangerous, humanly unmanageable, winds to exist in public spaces. It is common for incidents of this type to be settled out of court in order to avoid further publicity that may attract frivolous claims. Several incidents involving pedestrian wind accidents are reported each year in Boston, which may also indicate a greater frequency of reported incidents when a community is sensitized to the problem.

To avoid liability in urban wind incidents, it appears to be necessary for all parties associated with the design, development approval, construction, management and ownership of urban buildings to have taken all reasonable action to ensure that dangerous humanly unmanageable winds are not created by buildings. In some windy cities with long winter freeze conditions, such as Toronto, pedestrian access shifts to interconnected underground shopping complexes which reduce risk to pedestrians. Many of the pedestrian level wind control measures described above have been conceived under influence from community groups that have strong objections to tall buildings for other reasons unrelated to environmental wind effects such as pedestrian and traffic congestion and loss of sunlight. In a more logical environment there is no basis for placing blanket height restrictions on buildings to control street level wind environments. Building shape, spacing and height relative to surrounding buildings are the critical factors. Because of the infinite variety in the geometry of urban development, it is not possible to write general regulations based on geometric parameters to control undesirable street level wind effects without placing unnecessary restrictions on developers. For these reasons the most reasonable approach to urban wind control is to approve building projects on the basis of the results of wind tunnel studies that follow specified procedures and are assessed against established wind criteria.

Developers tend to argue that this approach will not allow them to know whether or not their proposal will meet the city's wind environment criteria until after a wind tunnel study is performed. A response to this argument is that most serious street level wind problems can usually be detected in a low cost preliminary wind tunnel study for a few thousand dollars using inexpensive foam plastic block models in the initial design stage of a project. Indeed at this stage it is common to compare the performance of a variety of building shapes and positions on a site. If such studies are not performed a developer can get into a position where commitment to a particular design leaves him no option but to reduce unacceptable wind conditions by adding expensive, unplanned appendages to his building. Detailed wind tunnel studies of the final design are still needed to measure probabilities of gust wind speeds for the final report to city authorities. As all estimates of the probability of occurrence of various wind speeds must be derived from long term wind data, city governments would be performing a valuable service if they had probability data prepared for their area. Most large wind engineering consultants have detailed wind data and wind tunnel models for many areas where there are buildings designed for wind. This helps to reduce the costs of wind tunnel studies.

Summer Breeze Penetration and Urban Heat Islands

City Planners and urban designers also need to be aware that demolition of existing buildings can significantly change the local wind environment; for this reason, site clearing options to create open public space and parks should be studied in wind tunnels. Positive aspects of urban ground level wind such as summer cooling and dispersion of vehicle exhaust fumes can also be studied in wind tunnels (ASCE 1999). Without by-laws or regulations to give legal status to city planners' requirements for wind tunnel study reports, probably only half of new projects would be tested. Public awareness has already been raised to the potential for undesirable wind effects created by large buildings and this awareness increases the risk of litigation.

In urban built environments in warm humid regions, landscaping can play an important role in achieving energy efficiency. Urban parks with mature shade trees can help to reduce the potential for development of urban heat islands by creating breezeways (Yeang1987) through urban environments. General recommendations on urban form in warm humid regions are for a general development of low 2 to 3 story high buildings in flood free areas facing wide open ended streets with shade trees (Awang et al. 1994). To mitigate urban heat island effects, trees are planted along the edges of roads as well as in a central median strip. Buildings should have light colored exteriors to reduce heat gain from the absorption of solar energy (Akbari et al. 1990). Urban heat islands make sleeping difficult without air conditioning in warm humid regions. Wind engineers can contribute to the optimum location of such breezeways as planned for in Kuala Lumpur, Malaysia.

CFD analysis of head island effect of the greater Tokyo area at 3:00PM were compared from August data for the years 1835 and 1995, Figure 7 (Murakami et al. 1999). In big cities it is actually common to observe nocturnal air temperature 3-4 °F higher than the surrounding areas, and in extreme cases, up to 8 °F higher. During the daytime hours, however, this difference in air temperature between the city and its surrounding area is smaller, only about 1-2 °F. The profile of temperature through a city shows its highest values roughly coincident with the central business district so that temperatures increase with building density (McBoyle 1970).

The intensity of the heat island is related more to the density of buildings rather than to city size (Chandler 1971) in a relatively small scale urban area. In most cases the density of buildings and energy consuming activities in the center of cities increase with the size of the city. Therefore, there is also a relationship between the size of the city and the intensity of the heat island in the city's centre.

In the cold climatic conditions of Sweden, it has been noted that energy consumption in the intra-city houses may be up to 20% less than on the exposed edge (Keeble 1990). This can be attributed to wind shelter, coupled with other elements of the urban heat island.

Natural Ventilation for Sustainable Urban Development

The harbor area of Rio de Janeiro, Brazil has undergone extensive revitalization as a means for urban sustainability (Laar 2004). Harbor functions are being relocated leaving an area of around 500000 m^2 available for redevelopment, Figure 8. Urban planners and designers have been developing schemes for mixed use including small scale industry and training, offices, commerce, residential, leisure and tourism. By increased residential density and mixed use neighborhoods, the scheme has the potential to drastically reduce vehicular traffic, since one third of residents will not commute by vehicle. With widely spaced high-rise buildings, the intention is to encourage natural ventilation instead of air conditioning. These high-rise buildings will also use façade integrated solar energy for hot water and electrical energy production. While quantitative studies of air flow through the development and resulting natural ventilation have not been performed to date, the intention is to use CFD studies to validate or modify the design for wind.

Urban energy efficiency in warm humid climates can be improved by encouraging multi-use building development to locate housing near places of employment and increasing population density with the introduction of slender, widely-spaced residential towers above the general 2 to 3 storey development (Joubert 1973). Wind engineers can contribute to the design of residential tower buildings so that they have greater potential for natural ventilation to provide indoor thermal comfort (Laar 2004). Increased urban population also improves the viability of public transport and allows urban residents to commute by foot or bicycle, as they do in New York City and most cities in Southeast Asia and Europe.

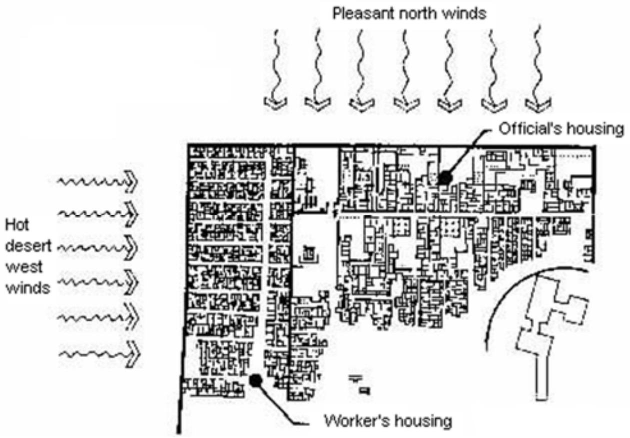


Figure 1. Egyptian town of Kahan and prevailing winds (Aynsley et al. 1977, with permission of Elsevier).

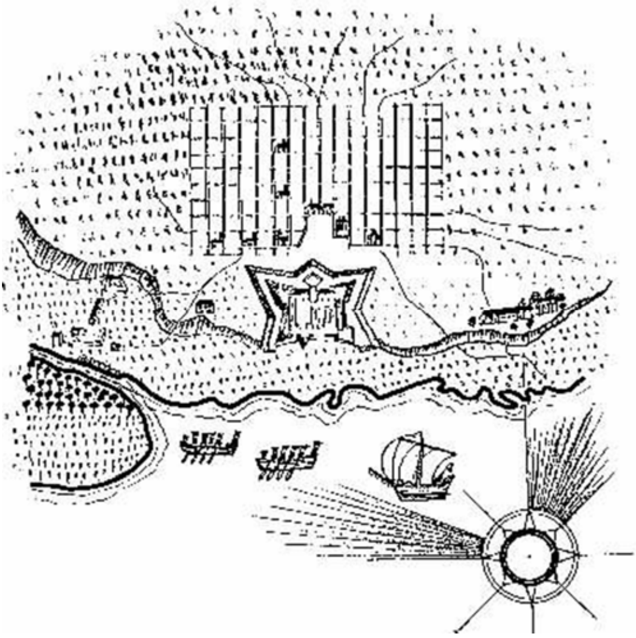


Figure 2. Buenos Aires and prevailing winds (Aynsley et al. 1977, with permission of Elsevier).

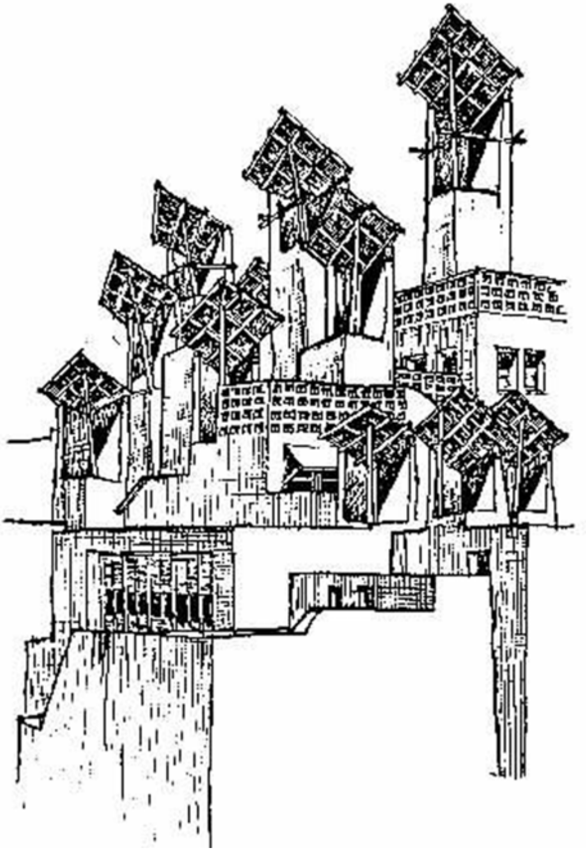


Figure 3. Wind scoops in city of Hyderabad (Aynsley et al. 1977, with permission of Elsevier).

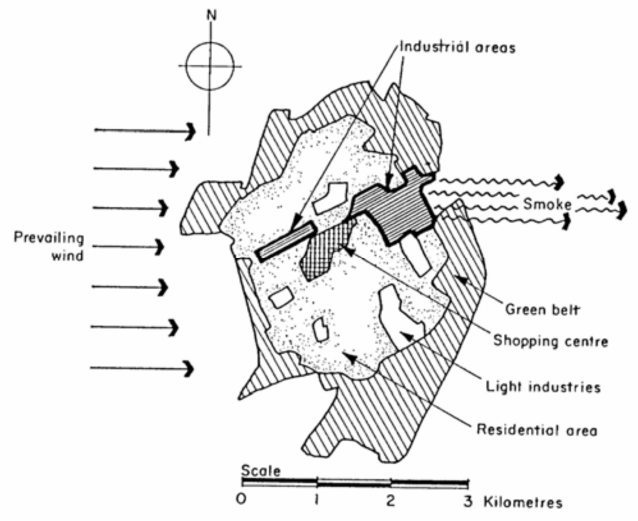


Figure 4. Plan of Letchworth indicating location of industrial areas relative to direction of prevailing winds (Aynsley et al. 1977, with permission of Elsevier).

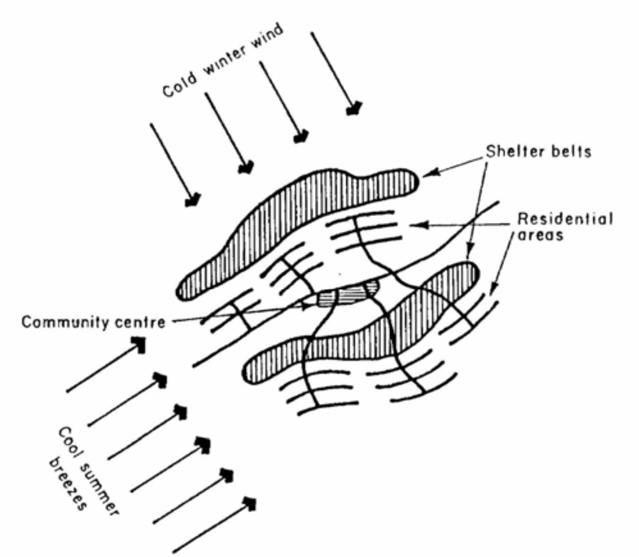


Figure 5. Forest shelterbelt configuration in dormitory town in New Jersey after Olgyay (Aynsley et al. 1977, with permission of Elsevier).

Figure 6. Man walking against strong wind, Wellington (Dominion Post Collection, Alexander Turnbull Library, Wellington, New Zealand, EP/1967/5183/12).

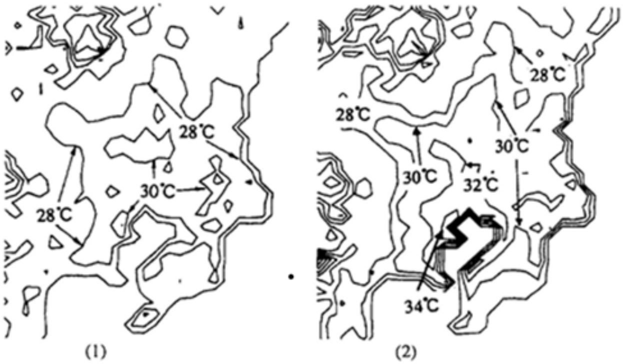


Figure 7. CFD analysis of heat island effect of the greater Tokyo area at 3:00 PM in early August in 1835 and 1995 (Murakami et al. 1999, with permission of Elsevier）.

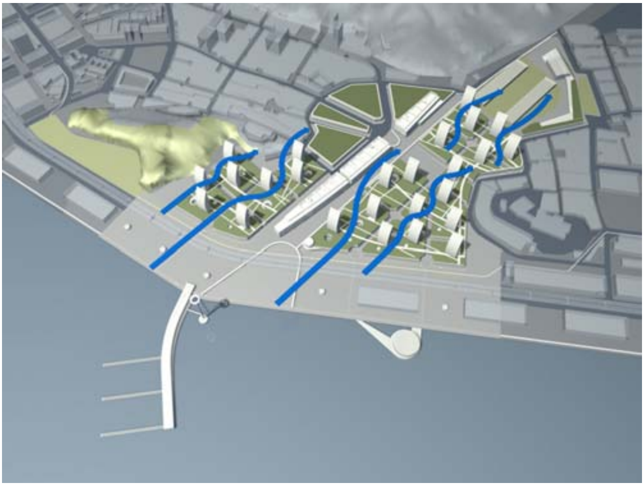


Figure 8. Proposed Harbor Redevelopment in Rio de Janeiro, Brazil with anticipated prevailing wind penetration (Laar 2004).

CHAPTER 3

WIND ENGINEERING IN URBAN AERODYNAMICS

URBAN HURRICANE AND TORNADO SHELTERS

Urban planners and designers need to consider the need for urban storm shelters in the event of extreme wind conditions such as hurricanes and even tornadoes. In some urban centers it is not always feasible to evacuate large populations when a hurricane approaches. In tall office buildings, walls of fire refuge floors can be economically designed to resist more extreme winds and windborne debris than is economic for walls on regular office floors. While the threat of tornadoes in urban zones has been largely downplayed, cities such as Miami (1997), Nashville (1998) and Fort Worth (2000) have recently experienced significant damage to high rise buildings due to tornadoes. The higher wind speeds and increased debris associated with tornadoes in urban zones create a more significant engineering design challenge (Figure 9). Where the risk of flooding is low, tornado shelters are frequently located in below-ground level space.

One of the consequences of Hurricane Andrew in southern Florida during 1992 is that many condominium buildings in the fifteen to thirty storey range are now being designed with balcony-edge storm shutters. Those shutters are intended to reduce the devastating damage that strong wind and rain can have when the building envelope is breached. In fact, recent experience in the United States suggests that residential damage claims are 40% larger when the building envelope is breached. The increase in internal pressure after cladding failure can create other cladding breaches on that floor or in that apartment. These events are frequently the cause of massive insurance losses. With the shutter option the prudent cladding designer is now interested in two physical geometries: (i) the open balcony condition (Figure 10) with no storm shutters present and (ii) the building with slab-edge storm shutters installed (Figure 11) (Cochran and Peterka 1999a). The latter effectively changes the shape of the building from a rough-surfaced collection of protruding balconies to a much cleaner, often rectilinear, structure.

The highest wind forces on the exterior of buildings are due to suction pressures near sharp-edged corners or roof edges. The negative cladding load variations with and without shutters are shown in Figures 12 and 13. Load variation is indicative of a pattern seen for exposed, mid-height buildings in Florida where the storm shutters effectively generate higher loads than a building with open balconies. The presence of many corner balconies results in typical, peak-negative, cladding loads along the corner strips of the walls being reduced by 35-40% when compared to the shuttered building, and 45–50% when compared to the ASCE.

Centrally located balconies on the wide face have no substantial impact on the positive or negative design pressures. In fact, the peak-positive pressures seem to be essentially unchanged by the presence of the storm shutters in the model studies. These observations may encourage designers to consider other design possibilities such as moving the storm shutters on the corner balconies to the glass face, or using impact-resistant glazing at these locations. In this way the designer can take advantage of the less coherent flow caused by the corner balconies and the resulting lower pressures. Another point to note is that if balcony-edge shutters are to be installed on an existing building, the designer should be aware that it is very likely the shutter loads created by this new corner geometry will be significantly greater than that experienced by the glass without the shutters. It should be noted that the presence of balconies does not automatically cause reduced cladding pressures. Some structures tested showed little or no negative-pressure reduction where wind flow separation can remain coherent along the vertical (often narrow) corner. As yet, there is no codifiable criterion for the influence of balconies, and recourse to wind-tunnel tests to demonstrate a load reduction is still necessary. Few office buildings have storm shutters (Figures 9 and 14)). The determination of wind loads on buildings from wind tunnel studies can often save costs of structural members that are often much larger when designed using more conservative but simpler wind loading calculations. These savings are often greater than the cost of a wind tunnel study.

PEDESTRIAN LEVEL WINDS

Some of the earliest problems of strong winds in pedestrian areas caused by tall buildings occurred in Boston. The 277 feet (84 m) high Earth Sciences building at MIT campus in Cambridge had an arcade through it at ground level. This arcade opening was 70 feet wide and 21 feet high through which frequent wind speeds of 80mph to 90 mph were experienced while wind speeds at level were only 40 mph to 50 mph (Koppes 1970). Similar problems were occurring downtown at Boston's Prudential Center. These tall buildings create a significant difference in air pressure between their windward and leeward faces when wind blows directly onto them. Any opening through the building offers an opportunity for air to flow rapidly from the high pressure windward region into the low pressure leeward region.

Parametric studies in boundary layer wind tunnels (Irwin 1981) and computational fluid dynamics (CFD) (Stathopoulos et al. 1992) shown in Figures 15, 16 and 17, have provided pedestrian level speed-up factors for some simple building geometries. These factors, K, are the ratio of locally increased wind speeds due to the presence of a tall building to the mean wind speed at that location without the building present. These studies often made use of the influence of scale, S, (Wilson 1989) (Figures 15, 16 and 17) which has been found to govern many pedestrian level wind conditions at normal wind incidence. This parameter is derived from the relative dimensions of the windward face of rectangular buildings, $S=(B_L B_S^2)^{0.33}$, where B_L is the larger and B_S is the smaller dimension of the windward face. The influence scale S becomes a constant when $B_L \geq 8B_S$. Buildings in urban environments are rarely in an isolated setting and wind tunnel studies or CFD computations are needed to predict pedestrian level wind conditions.

With local mean wind speeds predicted at pedestrian level around buildings, criteria for frequency of occurrence such as those indicated in Figure 18 (Melbourne 1978) can be used to determine if conditions are acceptable.

Wind engineering offers two methods for predicting the probability of high wind speed at pedestrian level near tall buildings. One method is to model the tall building and its surroundings in a boundary layer wind tunnel and measure the pedestrian level wind speeds. Data from such studies can indicate the probability of occurrence of wind gusts of various intensities, and also show how much wind gust speeds would increase (speed up), compared to conditions before the tall building is constructed. Similar studies can be conducted using computational fluid dynamics software on computers. These tools allow urban planners and designers to explore the impact of alternative urban development on wind conditions at pedestrian level before serious mistakes are made. Such mistakes can be very expensive and difficult to correct. These are discussed in detail in the companion ASCE booklet titled *Outdoor Human Comfort and Its Assessment* (ASCE 2003).

URBAN DESIGN FOR BREEZE PENETRATION

Higher air temperatures induced in urban environments by heat island effects can have serious consequences for vulnerable segments of the population such as infants and the elderly. Extensive surveys of deaths in North America attributed to high temperatures during heat waves showed mortality rates in excess of the norm with increases in air temperature, Weihe (Weihe 1985) documented mortality increases from negligible at 90°F through 75% at 100°F to 546% at 110°F.

High urban air temperatures can be mitigated by urban planning and design that promotes breeze penetration (Golany 1995; Evans and De Schiller 1996; Aynsley and Gulson 1999). Wind effects on urban heat islands have been mapped in Tucson (Comrie 2000). The urban heat island in Tokyo has been simulated by computer models (Saitoh et al. 1996).

Urban density may affect the ventilation conditions in the street and thus also the potential for natural ventilation of buildings. It is usually assumed that an increase in building density reduces the air flow in an urban area, which is a result of increased friction near the ground. However, this influence depends mainly on various physical details of urban space, including differences in heights of neighboring buildings and their orientation with regard to wind direction. The influence of these variables on wind on pedestrians and the dispersion of pollutants near ground level were studied with scaled models in boundary layer flow conditions (Isyumov et al. 1985).

WINTER WIND SHIELDING

One study within the British Isles, undertaken in Ireland and sponsored by the European Community Research and Development program, showed space-heating energy saving of around 5% for wind shelter effects alone (Keeble 1990). However, the height of windbreak used was two meters, protecting single-story buildings.

Trees and other vegetation are frequently used to ameliorate undesirable winds in urban areas. Heisler (1990) compared wind speeds in a field study of neighborhoods with and without trees and found that neighborhoods with a 77% deciduous tree density (by plan area) had a 43% wind speed reduction in winter and a 48% reduction in summer. Huang et al. (1990) used this data to estimate the potential heating and cooling energy saving from such wind shelter. Peak power savings were estimated at 3-20% for heating and 17-29% for summer cooling. Stathopoulos et al. (1994)

conducted a wind tunnel study of these shielding effects on low buildings. The study showed that with a single row of high density trees, air infiltration into low buildings four tree heights downwind was reduced by approximately 60%. This would correspond to winter energy savings of approximately 15%.

Obviously in high-rise urban centers it is possible to shape and orient large buildings so that much of the pedestrian level spaces are protected from strong chilling winds when they prevail from a particular direction. It is often the case that prevailing summer breezes come from a different direction, allowing designers to achieve the best for both climate seasons.

Another wind effect to be accounted for in urban regions with significant snow fall, is drifting snow. The geometry of buildings and the spaces around them will generate particular drift geometries depending on wind direction (Figure 19). These effects are often studied in wind tunnels by observing the scouring effect of wind on small lightweight particles (Livesey et al. 1990). The two principal concerns of snow drifts are the inconvenient accumulation of snow in busy pedestrian or vehicular routes and the distribution of snow accumulations on roofs for snow load considerations. Snow loads on roofs can be critical in the case of long-span roof structures (Figure 20). The most common method for predicting snow drift geometry is to seed water flow in a water tunnel (Figure 21), with small plastic pellets gauged to simulate the relative density of snow.

NATURAL VENTILATION OF HIGH-RISE OFFICE BUILDINGS

Potangaroa (2001) conducted a series of parametric boundary layer wind tunnel studies at James Cook University on models of rectangular office buildings of various heights with floor plan aspect ratios ranging from 1 to 3. Together with these external wind pressures, wind pressures were measured in vertical ventilation shafts open at roof level at the center of the models. At the time of these tests some architects were designing office buildings with extensive screens outside external walls. Wind pressures behind such screens were also measured and found to be highly negative with low porosity screens with the separating space open at roof level. This led to a wind driven natural ventilation scheme where an outer glazed wall formed a vertical space around the exterior of the building. This was combined with a rooftop air scoop that directed wind down a central ventilation shaft. The ventilating flow entered the rooftop scoop and passed down the central ventilation shaft or *air well* through wall openings at each floor. From there it crosses the office floors and passes out through windows on external walls and up the cavity or *air wall* between the external glazed screen and the office windows (Figure 22).

With appropriate geometry this *air-well-air-wall* air flow arrangement (Figure 22) can provide extremely efficient wind driven natural ventilation, even for office buildings wedged between adjacent buildings and with only a single external glazed wall.

Given the effectiveness of the *air-well-air-wall* arrangement a series of calculations of indoor thermal comfort were performed using hour by hour wind and air temperature and humidity data for a series of hypothetical office buildings. Air flow through office space 1 m above floor level was evaluated using CFD software (Figure

23). The results of these calculations were compared with estimates of thermal comfort in the same buildings designed for simple cross ventilation, Table 2. (Potangaroa and Aynsley 2000).

UMNO is the political party that has enjoyed majority status in Malaysia for many years. UMNO commissioned architects to design a 21 storey office headquarters building for UMNO in Georgetown. Natural ventilation wind engineers from Australia and the UK advised on how wing walls could be used to enhance indoor air flow given the direction of prevailing wind incidence on the building. Conceptual studies were evaluated using CFD studies of wind-driven indoor air flow.

Wind engineers conducted boundary layer wind tunnel studies, Figure 24, of the proposed new National Library building in Singapore. This sixteen storey building, to accommodate both library functions as well as public and cultural events, occupies a whole city block. The wind tunnel studies included conventional wind loads as well as pedestrian level winds around the building.

The boundary layer wind tunnel studies conducted at James Cook University in Australia were also used to determine environmental wind conditions in the pedestrian street through the complex, and upper-level garden areas (Figure 24). Critical periods for outdoor comfort in shaded locations were found from statistical evaluation of climate data for this humid tropical location to occur between noon and 6 pm during all months of the year based on 90% acceptance adaptive comfort criteria. Also studied were the probabilities of thermal comfort in the pedestrian street that was to run through the facility at street level. Percentages of time when thermal comfort would be unlikely were determined using wind speed coefficients referenced to long term wind speed records at Changi airport. As Singapore typically experiences significant periods of calm, as evidenced data for nearby Kuala Lumpur, Table 3, recommendations were made for the installation of large slow moving energy-efficient fans (600L/s.W) to draw large volumes of air down from roof level into the pedestrian street at low velocity during calm periods. Liddament et al. (2006) provide a review of naturally ventilated office buildings in UK and Europe.

NATURAL VENTILATION OF LOW-RISE BUILDINGS

Lee (1998a) evaluated the natural ventilation potential for indoor thermal comfort in a 1995 residential development in Townsville, Australia, that included small-lot housing. Until the 1980s a typical house site in Townsville had an area of about 700 – 1,000 m^2. In a recent 1995 residential development, the sizes of sites have been significantly reduced to 300 m^2 to 450 m^2. This reduces the potential for natural ventilation and creates a reliance on air conditioning for thermal comfort.

Parametric studies have been performed on arrays of cubic blocks representing simple houses showing the reduction of natural ventilation with increases in block density (Figure 25) (Lee et al. 1980). A model of portion of an actual Townsville subdivision, modeled at a scale of 1:200, was built to measure wind pressures on the walls of *carefully* modeled houses in a boundary layer wind tunnel (Figure 26).

Using wind frequency data together with air temperature and humidity at 3 hour intervals for January, the hottest month in Townsville, the percentage of time that indoor thermal comfort could be maintained by natural ventilation was computed. The indoor air velocity in living rooms and the master bedrooms in ten houses were estimated from wind pressures on the surface of solid model houses. Some general observations from this research were:

1) Houses in the development were designed without consideration of natural ventilation.
2) House designs were frequently reversed in plan to create more visual variety without consideration of natural ventilation.
3) Area of the site occupied by semi-detached houses ranged from 41% to 47%. This equates to an overall land coverage density of over 33% when roads are taken into account (category C for normal spacing in Figure 25).
4) Area of the site occupied by two storey terrace houses ranged from 26% to 29% with enhanced spacing that allows for staggering houses and increased potential for natural ventilation (category B for staggered spacing in Figure 25).

Six out of the ten living rooms had good ventilation potential for indoor thermal comfort (>95%) at 3:00 PM. The remaining four living rooms had less than65% ventilation potential for indoor thermal comfort. Only two bedrooms had satisfactory ventilation potential (>78%) for indoor thermal comfort at 9:00 PM, when people try to sleep. The remaining bedrooms could only achieve less than 69% ventilation potential for indoor thermal comfort and require air conditioning. Houses designed by architects to benefit from natural ventilation often achieve more than96% ventilation potential for indoor thermal comfort at 3:00 PM in Townsville but ceiling fans are needed at 9:00 PM when winds become calm (Lee 1998a).

HUMAN THERMAL COMFORT IN NATURALLY VENTILATED SPACES

The ASCE published a booklet on Outdoor Human Comfort (ASCE 2003) that discusses thermal effects and describes approaches for assessing thermal comfort. There are additional references specifically dealing with comprehensive comfort criteria including thermal effects (Wiliams et al. 1992; Soligo et al. 1998). The approach described in these papers has been used on a large number of projects, primarily in hot climates including Burj, Dubai.

For the first time the ANSI/ASHRAE Standard 55 (2004) for assessing thermal comfort in air conditioned space introduced an alternative method for evaluating thermal comfort in naturally conditioned spaces. Naturally conditioned spaces are defined as *those spaces where the thermal conditions of the space are regulated primarily by the opening and closing of windows by the occupants*. The adaptive model used was that developed by de Dear and Brager (2001) ANSI/ASHRAE Standard 55 (2004) provides a graph indicating ranges of air temperature to satisfy thermal comfort of 80% of an acclimatized population, based on mean monthly temperature generally recommended for design purposes (Figure 27).

The 2005 ASHRAE Handbook of Fundamentals (ASHRAE 2005) included more information on adaptive thermal comfort. These handbooks give equations for calculating the temperature for operative comfort.

Wind engineers can play an important role in urban planning and design by offsetting heat island effects in urban areas with appropriate breeze penetration. The cooling effect of air flow past exposed skin is approximately 3.6°C for each m/s of air flow. This means that a strong breeze of 2 m/s can have a cooling effect of around 7.2°C which can be subtracted from the dry bulb air temperature to give the equivalent still air temperature. In most urban areas the mean pedestrian level wind speed is significantly less than in surrounding rural areas. Wind speeds in office space are often controlled to around 1 m/s to avoid dislodging loose paper on desktops.

BACKUP FOR WIND-DRIVEN NATURALLY VENTILATED SPACES

If wind-driven natural ventilation for indoor thermal comfort is to compete effectively with central air conditioning in warm humid regions, evaluation of its effectiveness must be extended to accommodate backup mechanical air movement from fans during periods of calm (Figure 28). To accomplish this, natural ventilation needs to be assessed in terms of the percentage of time that it is likely to be effective in maintaining indoor thermal comfort.

For that period of time when wind-driven natural ventilation is not likely to be sufficient, a mechanical back up system should be designed. The cost of this system, together with its cost of operation, will be needed to enable meaningful comparison with costs of air conditioning systems and their operating costs. Without such information it is difficult to present a convincing case for wind-driven natural ventilation.

Where circulator type fans are used, large, high-volume, low-speed fans have the potential to be far more energy-efficient than smaller higher speed fans (Aynsley 2005). This high energy-efficiency in movement of air, up to 1200 cfm/W, results from the generally higher energy-efficiency of propellers at low-speed combined with the use of low-drag airfoil fan blades mounted at an optimal angle of attack.

DISPERSION OF URBAN AIRBORNE POLLUTANTS

The complex relationships between buoyancy and wind pressure forces during fires can be modeled using CFD software. Studies using this technique can be used to assess the efficiency of vent openings and the flow path of exhausted smoke. Exhausted smoke can sometimes re-enter the building if the smoke plume reattaches to the building near another building opening. CFD studies can indicate appropriate spacing of vents and other openings to avoid such re-entry under various wind conditions. Wind tunnel or CFD studies can be used to determine the optimum location for fresh air intakes for HVAC systems with respect to wind pressure and pollution sources such as vehicular exhaust fumes and kitchen exhausts.

Of more interest to urban planners and urban designers are expanded studies. Such studies can consider potential propagation of smoke and toxic fumes released from research facilities at universities and medical facilities, Figure 29. Plumes from industrial accidents can also be modeled using tracer gas techniques in boundary layer wind tunnels or CFD computer software. Figure 30 is a visual display of a potential toxic plume moving down a valley in rough terrain toward a nearby city. These displays using flow visualization are not used to quantify toxics; other studies that measure toxic concentrations in parts per million using tracer gases are used for that purpose.

DISPERSION MODELING IN BOUNDARY LAYER WIND TUNNELS

Flow and dispersion over urban settings are affected by temperature gradients within the urban area and outside the urban boundaries as well as by non-uniform roughness and topography (Oke 1979; Landsberg 1981). Two primary length scales for turbulence result from temperature differences developed by the urban complex itself: (1) the differences between surface temperatures over the urban area and the surrounding surface area that form the urban heat island, and (2) temperature differences between street and building surfaces. The former gives rise to flow perturbations of overall urban dimensions (Sethuraman and Cermak 1974) while the latter generates local naturally-convective flows of building height and street-width dimensions which are strongly modified by wind driven forced convection (Numez and Oke 1977; Wedding et al. 1977).

Temperature differences, between air in the boundary-layer flow approaching the urban area and the upwind surface, cause flow approaching the urban area to be thermally-stratified, affecting flow and dispersion over the urban area (Sethuraman and Cermak 1975). Air-surface temperature differences over sloping terrain result in upslope and down-slope winds that materially affect the urban wind field and dispersion (Petersen et al. 1980). As discussed by Changnon (1992), significant local weather modifications have been attributed to these large-scale effects.

Physical modeling in a boundary-layer wind tunnel provides a convenient and economical method for systematic investigation of thermal effects on urban flow fields and dispersion. In particular, a wind tunnel able to simulate stratified boundary layers (stable unstable and elevated inversions) offers many possibilities for flow and dispersion studies (Cermak 1981). The following presentation is confined to physical modeling of overall thermal effects on flow and dispersion over urban areas caused by large-scale temperature differences (the “heat island”) and thermally stratified or thermally driven approach flow. A discussion of the processes involved is presented in a paper by Oke et al. (1991).

DISPERSION MODELING WITH COMPUTATIONAL FLUID DYNAMICS

A number of studies have indicated that modeling of dispersion of vehicular emissions in an urban street canyon using CFD with the k-ε turbulence model was in approximate agreement with result from boundary layer wind tunnel studies. The difficulty with wind tunnel studies is that all the significant processes involved need to be scaled in a consistent manner so that their interaction within the wind tunnel reflects conditions at full-scale. The problem with numerical models is that they include within their mathematical formulation only a few of the principal processes at work. A recent study by Johnson (1999) found that the k-ε turbulence model may underestimate the turbulent dispersion taking place, especially near solid surfaces. Corrections based on wind tunnel data were suggested as a means to correct the CFD output.

Terrorist threats have prompted the US Department of Homeland Security to sponsor studies of dispersion patterns in a number of US cities (USDHS 2005). These urban security projects include CFD modeling as well as validation field studies using tracer gas releases (NRC 2003).

URBAN WIND POWER

A quick search on the Internet under *wind and urban design* will reveal many sites with information on cities considering using wind turbines. Wind turbines are an increasingly common sight in wind farms in rural settings. In urban settings land is a precious commodity. It is for this reason that engineers and urban designers have been exploring the feasibility of integrating wind turbines into high-rise buildings (Hartman 2001).

Some of the issues that arise when integrating wind turbines into buildings are:

- Noise and vibration from turbines
- Need to direct wind from varying directions toward the turbines
- Optimizing location of turbines to catch higher wind speeds, and;
- Aesthetics

Orientation of the towers is a compromise alignment with respect to the dominant prevailing wind directions. This means that some wind energy from other wind directions cannot be harvested. The turbines tend to be located as high as possible to take advantage of the general increase in wind speed with height above ground. At the design stage, wind engineering techniques are used to quantify the potential of future wind events to contribute wind energy to the turbines.

Table 2. Relative Effectiveness of Conventional Natural Ventilation and Air-Well-Air-Wall Natural Ventilation in Maintaining Indoor Thermal Comfort (Potangaroa and Aynsley 2000, with permission of Elsevier, University of Reading, U. K.).

Geographic Location	Conventional Natural Ventilation	Air-Well-Air-Wall Ventilation
Kuala Lumpur	15%	34%
Singapore	40%	60%
Jakarta	45%	72%
Hong Kong	85%	92%
San Francisco	7%	9%
Los Angeles	17%	19%

Table 3. Percentage of calms by month at three hourly intervals for Kuala Lumpur, Malaysia (Courtesy of Richard Aynsley).

Note: Calms represent winds less than 1.4 m/s for wind records
10m above ground level based on data from 1965 to 1975.

Hour of Day	3:00 AM	6:00AM	9:00AM	12:00Noon	15:00PM	18:00PM	21:00PM	24:00Mn	Ave.
Month									
Jan	72%	38%	28%	87%	96%	96%	95%	97%	76%
Feb	68%	32%	23%	88%	95%	96%	98%	99%	75%
Mar	64%	33%	17%	87%	95%	95%	98%	98%	73%
Apr	67%	33%	33%	88%	97%	96%	95%	96%	76%
May	50%	21%	27%	90%	95%	94%	90%	92%	70%
Jun	40%	19%	30%	91%	96%	95%	91%	94%	70%
Jul	34%	20%	24%	91%	96%	94%	93%	88%	68%
Aug	36%	19%	25%	88%	95%	93%	89%	90%	67%
Sep	44%	17%	25%	89%	92%	92%	92%	90%	68%
Oct	53%	20%	35%	90%	94%	92%	89%	89%	70%
Nov	63%	30%	39%	91%	94%	91%	93%	93%	74%
Dec	77%	45%	40%	90%	95%	95%	93%	95%	79%
Ave.	56%	27%	29%	89%	95%	94%	93%	93%	

Figure 9. Other office buildings were severely damaged by hurricane Wilma. (Courtesy of Steven Camposano).

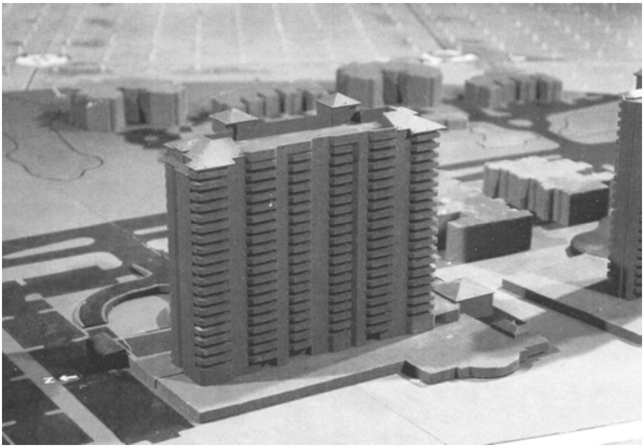


Figure 10. A CPP 1:300 model of a condominium in Naples, Florida open balconies (Cochran and Peterka 1999b, with permission of International Association of Wind Engineering).

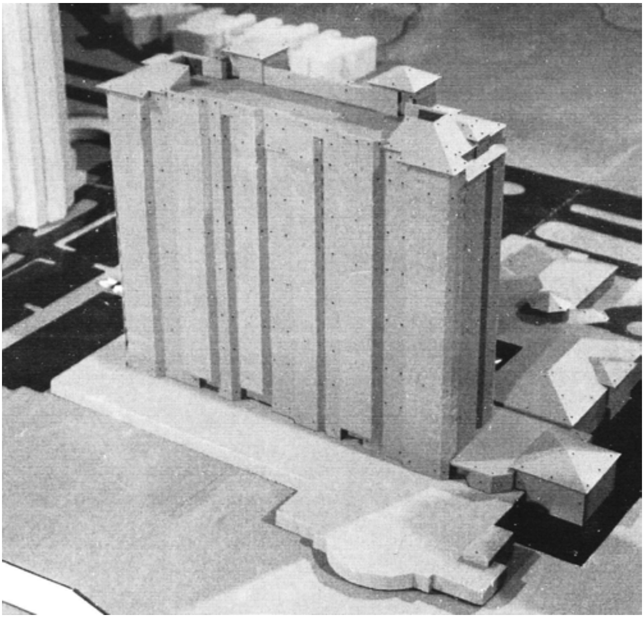
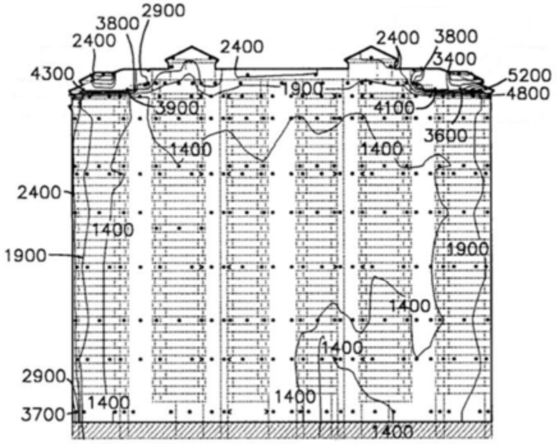


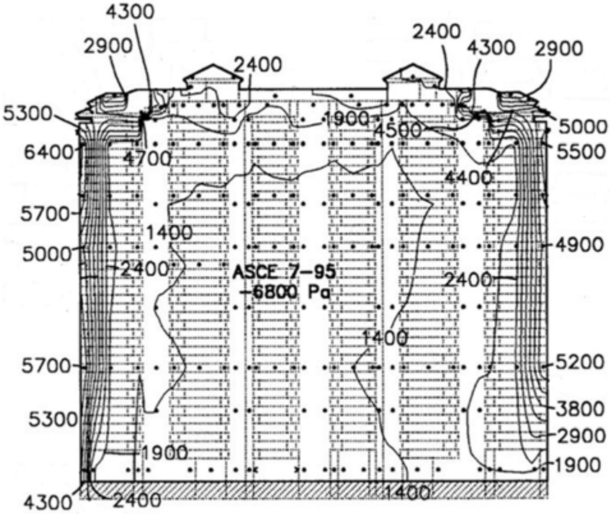
Figure 11. A CPP Naples condominium model configuration in Naples, Florida with storm shutters (Cochran and Peterka 1999b, with permission of International Association of Wind Engineering).



WEST ELEVATION

WITHOUT STORM SHUTTERS

PEAK NEGATIVE EXTERNAL CLADDING PRESSURES (Pa)



WITH STORM SHUTTERS

Figures 12 and 13. Peak cladding pressures determined from a boundary layer wind tunnel study for condominium with and without storm shutters (Cochran and Peterka 1999b, with permission of International Association of Wind Engineering).

Figure 14. Wind engineered storm shutters protected this condominium building from hurricane Wilma (Courtesy of Steven Camposano).

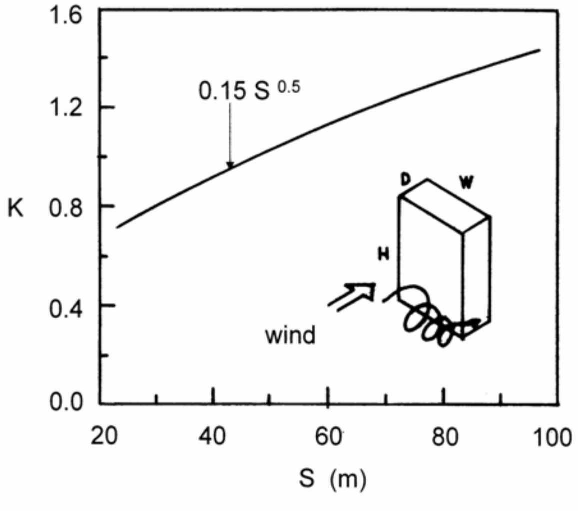


Figure 15. Frontal vortex speed-up factors for wind normal to a slab type buildings with respect to scaling factor *S* (Stathopoulos et al. 1992, with permission of Elsevier).

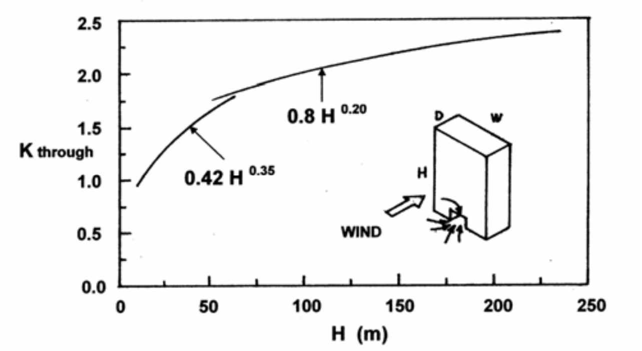


Figure 16. Flow through portal speed-up *K* factors for wind normal to a slab type building with respect to building height (Stathopoulos et al. 1992, with permission of Elsevier).

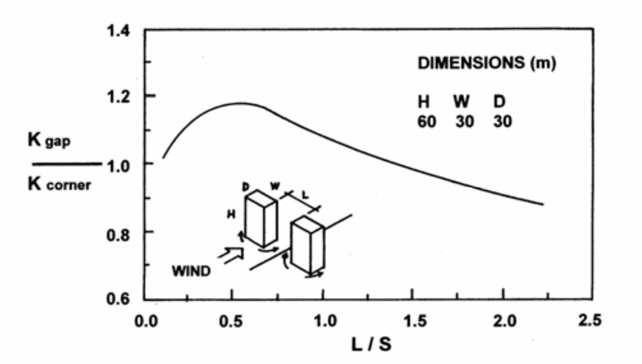


Figure 17. Gap to corner speed-up ratios for wind normal to slab type buildings with respect to spacing/scaling ratio *L*/*S* (Stathopoulos et al. 1992, with permission of Elsevier).

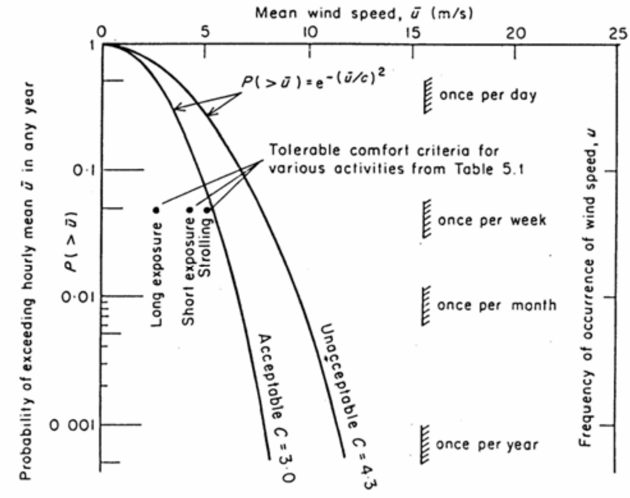


Figure 18. Pedestrian level wind acceptance criteria (Melbourne 1978, with permission of Elsevier).

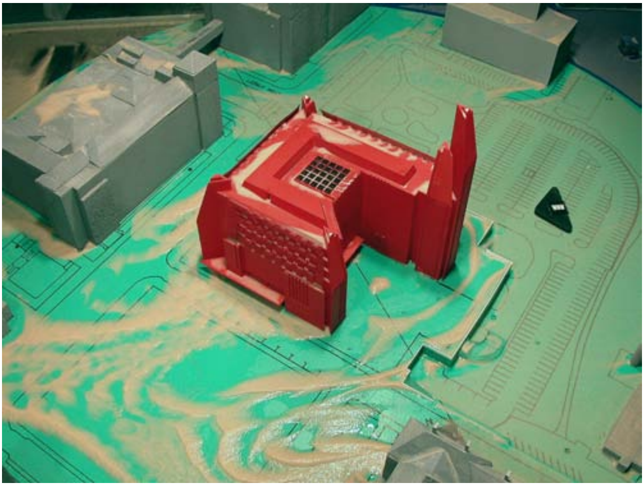


Figure 19. Urban snow drifts modeled in a water tunnel (Courtesy of Rowan Williams Davies and Irwin Inc. Guelph, ON Canada).

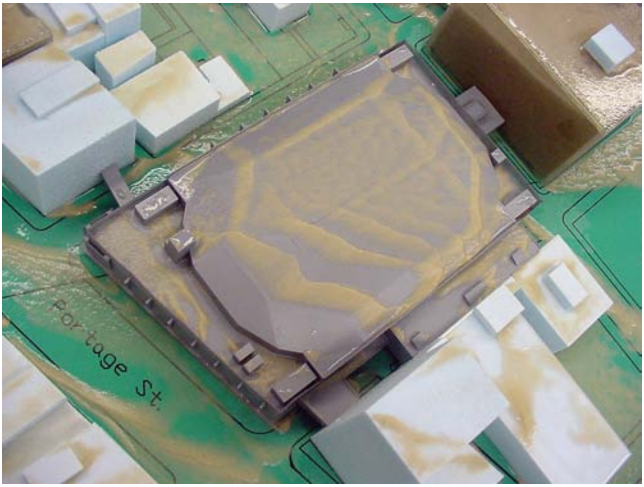


Figure 20. Snow drift pattern on a long span roof (Courtesy of Rowan Williams Davies and Irwin Inc. Guelph, ON Canada).

Figure 21. Water tunnel for snow drift modeling at RWDI (Courtesy of Rowan Williams Davies and Irwin Inc. Guelph, ON Canada).

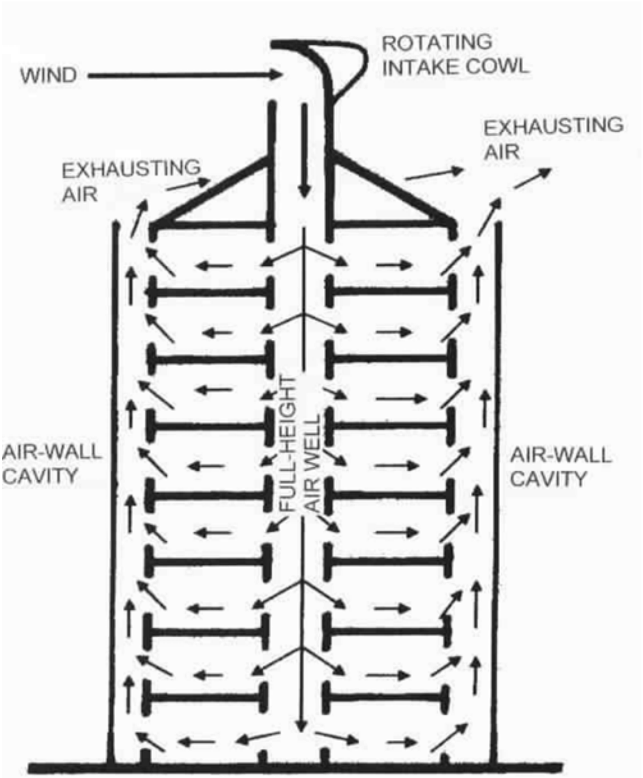


Figure 22 Air-well to air-wall ventilation for a tall building (Courtesy of Richard Aynsley)

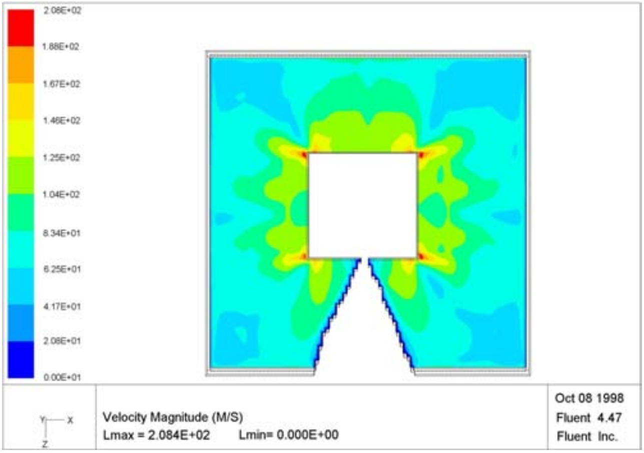


Figure 23. Air Velocity Contours inside Office Space with Air-Well-Air Wall Ventilation Using CFD Software (Potangaroa 2001, with permission of Regan Potangaroa).

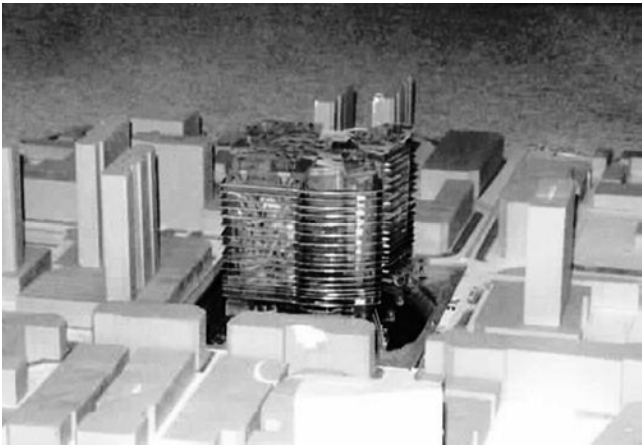


Figure 24. Model of the National Library, Singapore model in a boundary layer wind tunnel (Courtesy of Richard Aynsley).

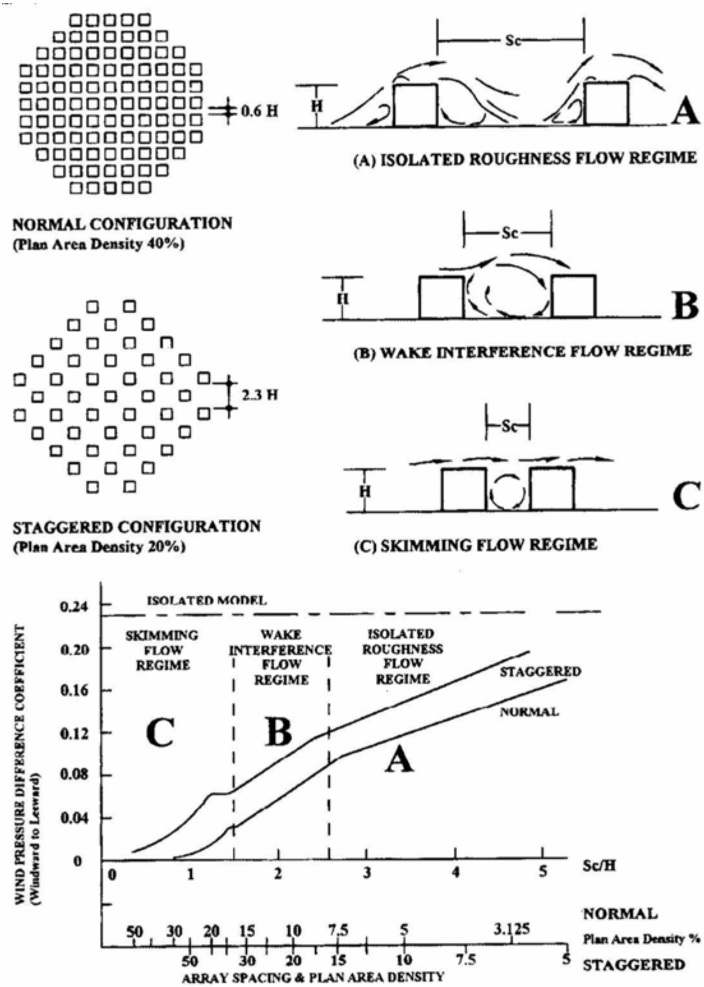


Figure 25. Influence of building density on natural ventilation potential (Lee et al. 1980, with permission of ASHRAE Journal).

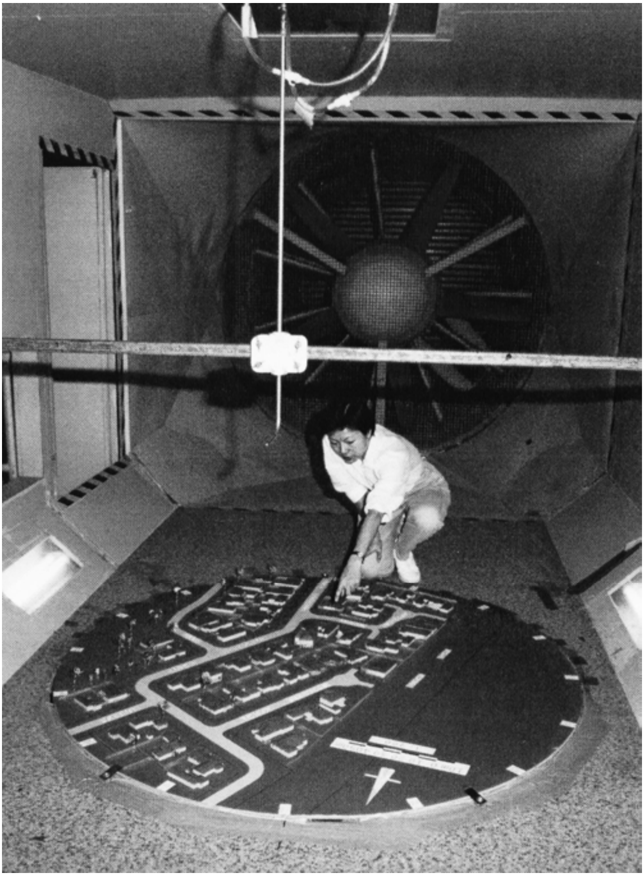


Figure 26. Residential development model in boundary layer wind tunnel (Lee 1998b, with permission of Susan Lee).

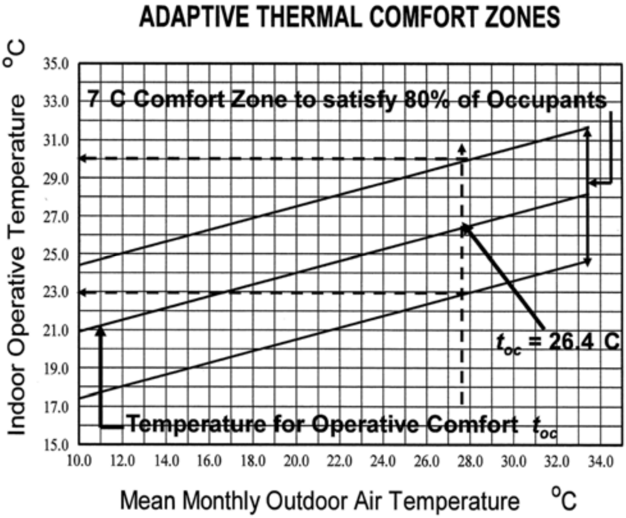


Figure 27. 80% Acceptability Limits for Indoor Operative Temperature based on ASHRAE Adaptive Comfort Model for Naturally Conditioned Spaces (Courtesy of Richard Aynsley).

Figure 28. High-Volume Low-Speed Energy-Efficient Ceiling Fans (Courtesy of Big Ass Fan Co.).

Figure 29. Flow visualization of exhaust plume from a hospital stack (Courtesy of Cermak Peterka Petersen (CPP) Inc.).

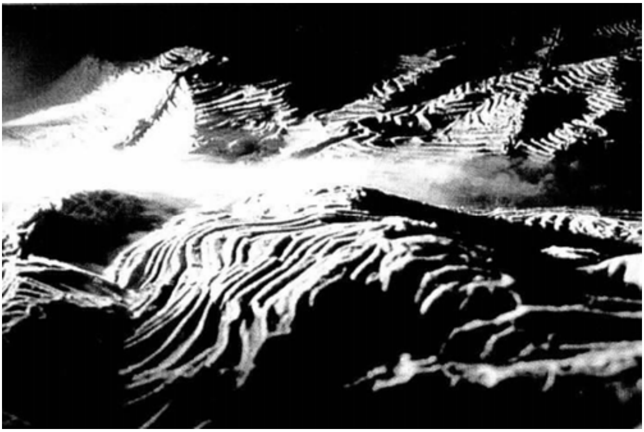


Figure 30. Flow visualization of a toxic plume flowing down a valley toward an urban center （Courtesy of Cermak Peterka Petersen (CPP) Inc.）.

CHAPTER 4

TOOLS AND TECHNIQUES

FLOW VISUALIZATION

Air flow through models of urban environments in wind tunnels is invisible unless visualization media are introduced into the air flow. The most common media is smoke or other dense fumes such as titanium tetra chloride (Figure 31). These media are often difficult to photograph particularly when their density is too high or too low. Also dense smoke in the foreground can obscure smoke in the location of most interest to viewers. Other media such as flexible fiber tufts or threads can be attached to surfaces to indicate flow close to those surfaces (Figure 32) or attached to the end of a moveable wire probe to observe airflow direction and turbulence in space away from surfaces. Lightweight granular materials such as granulated cork or expanded polystyrene beads are often used to observe ground surface air flows in pedestrian areas in models of urban spaces (Figure 33).

QUANTIFYING WIND EFFECTS

Any assessment of wind effects in urban environments needs to take account of the natural variability of wind. Wind engineering is essentially the estimation of the statistical probability of a specific wind effect occurring. Detailed wind frequency data collected at airports over periods of 20 to 30 years are the most common source of wind data used to determine the relative probability of wind events at a particular location (Figure 34). This approach is necessary to determine the level of risk associated with the potential damage or benefit of an urban wind effect.

Probabilities of wind events at other locations distant from an airport can be determined from wind tunnel studies, referenced to the airport location where there are significant topographic features such as mountains between the airport and the site. When the terrain is generally flat, calculations can be used, that take into account of changes in ground surface roughness created by buildings and vegetation and distance between the airport and the site.

BOUNDARY LAYER WIND TUNNELS

The benefits of wind engineering were first affirmed for tall structures, since measurements of load effects by high frequency force balance or aeroelastic models were requisite for their design (Isyumov 1982; Tschanz and Davenport 1983). The design of these structures also may utilize wind tunnels, Figure 35, for quantification of wind pressures on exterior cladding and pedestrian level winds. The tools and techniques developed by professional wind engineers to make the latter set of measurements also enable the prediction and quantification of wind effects in urban developments before the building is constructed, allowing designs to be changed to achieve a more favorable wind environment (AAWE 2005).

A windy environment around the base of a building, particularly near a main entrance or plaza area, will detract from the appeal of the site and perhaps discourage clients and shoppers from visiting the area. Similarly, an outdoor pedestrian space, such as a recreational pool area of a residential condominium, should be protected from strong mean winds. Thus, there is a direct financial motivation to ameliorate the wind environment if it is going to adversely impact the appeal of a tenanted building. In the extreme case a site may be dangerous, particularly to the infirmed.

At calmer wind speeds the issues may be quite different. The motivating concern may be the removal of stale air and/or viruses, like SARS, from the populated areas of cities with many tall, closely spaced buildings. Even the location of local air intakes, to avoid noxious or unpleasant odor sources, can be explored in the wind tunnel. Many factors will have an impact on the wind conditions around a building or within the whole downtown cityscape. The parameters may include: the ambient wind statistics, local topography, building massing, nearby foliage and proximity to similarly tall structures. It is for this reason that many new-building designers evaluate their project in a boundary-layer wind tunnel to inspect an individual building within the cityscape (scales 1:200 to 1:500). However, the city planner may wish to explore the future optional massing choices for the whole downtown (scales 1:1000 to 1:4000) (Figure 36) in a more generic sense to decide where to encourage growth, and at what heights and densities, in the coming decades (Givoni 1997).

A detailed manual exists on engineering practice for the boundary layer wind tunnel studies. *Wind Tunnel Studies of Buildings and Structures* (ASCE 1999) published by the American Society of Civil Engineers, deals mainly with boundary layer wind tunnel studies to determine wind loads. However it also includes two sections relevant to urban planning and urban design. One section deals with pedestrian level winds, and another on dispersion of airborne pollutants.

The use of small-scale models, Figure 36, in a boundary-layer wind tunnel, has been routinely used to study the effects of terrain and complex cityscapes on airflow at ground level, and at elevation, in downtown areas or both high-speed pedestrian-winds and for the removal of stale or polluted air (Cochran and Howell 1990).

WIND TUNNEL MEASUREMENTS

Wind tunnels are used not only for visualization of flow fields in urban zones, but also for quantification of aerodynamic effects through distributed measurements of wind velocity and pressure (Isyumov 1972). To simplify scaling considerations, all data measured in wind tunnels is reduced to dimensionless ratios or *coefficients*. In the case of wind pressures at a point on a surface, the pressure measured at that point in the wind tunnel is divided by the dynamic pressure, $1/2\rho v^2$, exerted by the approaching reference wind at a specified height above ground level (where ρ is the density of air, and v is the velocity of the air in consistent units). This ratio, $p/(1/2\rho v^2)$, is referred to as a *pressure coefficient*. In the case of wind speeds at a point, the wind speed measured at that point in the wind tunnel, V_1, is divided by the wind speed, Vr, of the approaching reference wind at a specified height above ground level. V_1/Vr, is referred to as a *wind speed coefficient*. All such measurements are tied to probability of occurrence associated with long-term wind data.

The time-averaged wind flow pattern around sharp-edged rectangular buildings (*bluff bodies*), for a particular wind direction, does not change over a wide range of wind speeds. Using a coefficient approach allows wind pressures or wind speeds at particular points to be calculated from a single pressure coefficient or wind speed coefficient for a range of reference wind speeds.

In the case of buildings or other structures with smooth curved surfaces, time-averaged air flow patterns are likely to change with increases in wind speed as the air flow over the surface detaches and sometimes reattaches at different locations. The detachment of flow from the surface is governed by the ratio of the dynamic force to the viscous force at that point in the flow. This ratio is the Reynolds number, *Re*. It can be very difficult to achieve all the scaling factors for wind tunnel models of buildings with smooth curved surfaces. For this reason wind engineers will often advise urban designers to have protrusions, such as protruding columns, on such smooth curved surfaces. These protrusions ensure that the surface flow separates at particular points on the surface, regardless of wind speed or direction.

Validation of Boundary Layer Wind Tunnel Studies

An obvious question urban planners and designers have is how accurate boundary layer wind tunnel studies of pedestrian level winds in urban environments are. Vickery (1992) conducted such a study at 1:400 scale comparing three months of one minute time-averaged wind records at a local airport with pedestrian level winds in a small park in nearby southeastern US city. Buildings around the park varied in height from 150 ft to 600 feet.

Wind conditions at pedestrian level were measured in the park and compared with those predicted by the wind tunnel study. The comparison was qualitatively very good, with both data sets showing simultaneous peaks and valleys of gusts. The fluctuations in the estimated wind speeds were greater than those measured on site. This was attributed to differences in the averaging times. Over a three month period the mean predicted and mean measured wind speeds differed by only 4%.

COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) is increasingly being used to address problems in urban aerodynamics. Urban Aerodynamics simulations generally involve large computational domains with many computational cells or control volumes. Knowledge of the flow behavior and of the subsequent minimal grid resolution requirements for the sub-configurations is important to arrive at optimal mesh resolutions and accurate and economical simulations for the urban environment as a whole.

There is a variety of CFD methods they can apply to evaluate the turbulent flow around buildings in the urban environment: Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds-averaged Navier-Stokes simulation (RANS). In addition, hybrid approaches, such as Detached Eddy Simulation (DES) are available. DNS requires very extensive computational resources and can at present only be applied for flow in simple geometries and at low Reynolds numbers. For the complex high-*Re* number flows in urban aerodynamics, application of DNS will not be possible in the foreseeable future. LES is a simplified method in which the spatially filtered Navier-Stokes equations are solved. RANS refers to the approach with equations obtained by averaging the Navier-Stokes equations (time-averaging if the flow is statistically steady or ensemble-averaging for time-dependent flows). With RANS, only the mean flow is solved while all scales of turbulence have to be modelled. The averaging process generates additional unknowns for which turbulence models are required. Many turbulence models are available, but there is no single turbulence model that is universally accepted as being the best for all types of applications.

The statistically steady RANS method is the one that has been most widely applied and validated in computational urban aerodynamics. It has been used for a wide range of building applications including estimating pressure coefficients (Murakami et al. 1992; Richards and Hoxey 1992; Stathopoulos and Zhou 1993; Stathopoulos 1997; Oliveira and Younis 2000; Meroney et al. 2002), wind-driven rain (Choi 1993; Choi 1994; Blocken and Carmeliet 2002, Blocken and Carmeliet 2004; Tang and Davidson 2004), pollutant dispersion (Dawson et al. 1991; Cowan et al. 1997; Leitl et al. 1997; Li and Stathopoulos 1997; Meroney et al. 1999; Meroney 2004), pedestrian wind conditions (Stathopoulos and Baskaran 1996; Richards et al. 2002; Yoshie et al. 2007), snow drift (Sundsbo 1998; Thiis 2000) and cooling tower drift (Meroney 2006; Meroney 2008). Although many applications of RANS in the past have been limited to isolated buildings or relatively simple building arrangements, significant differences have been found in comparisons with wind tunnel and full-scale measurements in specific cases. These are attributed to turbulence model limitations and to the statistically steady solution of flows that exhibit pronounced transient features, such as intermittent separation, recirculation zones and vortex shedding. In addition, a wide range of other computational aspects can contribute to uncertainties and errors, divided by Franke et al. (2007) into two broad categories: physical and numerical. Physical modeling errors and uncertainties result from assumptions and approximations made in the mathematical description of the physical process.

LES is a time-dependent approach in which more of the turbulence is resolved. It therefore has a larger potential to provide accurate results than statistically steady RANS simulations (Murakami et al. 1992; Tominaga et al. 1997). LES also provides more information about the flow, such as instantaneous and peak wind speeds, pressures and pollutant concentrations. However, it requires considerably higher CPU times and memory than RANS. It also requires time and space resolved data as boundary conditions to properly simulate the inflow. Such experimental data are rarely available in practice (Franke et al. 2007). LES is also considered to require more experience for users to apply effectively than does RANS. Consequently, the practical application of computational urban aerodynamics will continue to be based on statistically steady RANS for a considerable time to come.

Recently, various sets of guidelines for the use of CFD have been developed and assembled to help users avoid, reduce and estimate the errors and uncertainties in applying CFD. Casey and Wintergerste (2000) have provided a very extensive set of guidelines for industrial CFD applications, many of which are also applicable to computational urban aerodynamics. Franke et al. (2007) have assembled a comprehensive best practice guideline document for the CFD simulation of flows in the urban environment. Also, recommendations for particular applications such as pedestrian wind conditions around buildings have been developed (Mochida et al. 2002; Yoshie et al. 2007). Other efforts have focused on specific problems in CWE, such as those encountered in simulating equilibrium atmospheric boundary layers in computational domains (e.g. Blocken et al. 2007a; 2007b; Hargreaves and Wright 2007; Yang et al. 2008). Most of these guidelines apply to statistically steady RANS simulations.

Independent of whether RANS or LES is employed, evaluating the accuracy of CFD results by comparing them with wind tunnel or field experiments is very important because turbulence models are based on assumptions and no turbulence model is universally valid for all applications. Physical modeling therefore remains an indispensable tool in all applications of wind engineering.

One of the most common sub-configurations is a passage between two parallel buildings. In the past, CFD for wind speed in passages between buildings has been conducted by many authors. However, for the specific situation of wind flow parallel to the passage between two generic buildings of equal height, relatively few numerical studies have been made. In particular, grid resolution guidelines are limited. In a recent comprehensive publication of recommendations for CFD simulations of the pedestrian wind environment, Franke et al. (2004) mentioned that an initial minimum grid resolution guideline for the built environment is to use at least 10 cells per cube root of the building volume and at least 10 cells per building separation. A grid-sensitivity analysis starting from these initial guidelines is recommended.

Wind engineering studies of wind speed in urban spaces that are used to assess pedestrian thermal comfort may not indicate that the air in wake regions is re-circulating in eddies. This can be problematic with respect to ensuring fresh air in outdoor spaces. Some CFD software is able to trace the paths of specific parcels of air and indicate the *age of air*, or length of time the parcel has occupied a particular region in the air flow.

Teams of urban designers, planners, architects and wind engineers collaborate to explore quantitative estimates of air flow through alternative design proposals. An example of the potential for natural ventilation and pedestrian comfort in high-density housing can be found in the Vanke Doushi Garden development in Beijing, which is currently exploring the use of CFD techniques (Jiang et al. 2005). The final design has a wall of high-rise apartments 33m to 90 m high to shelter smaller buildings from the chilling winter winds at over 7 m/s from the north. This design maintained natural ventilation from pleasant southerly breezes during summer months. Acceleration factors for ground level winds in schemes for urban development can be found from CFD analysis. Finally, Figure 37, taken from van Hooff and Blocken (2010), shows wind speed amplification factors evaluated from a CFD analysis of wind flow around a stadium in the wake of other buildings in an urban environment.

FIELD STUDIES

Street intersections are often the windiest locations in urban environments. A wintertime survey of more than 300 pedestrians' perceptions of environmental conditions was conducted between 10:00 AM and 2:00 PM in Sydney, Australia (Aynsley 1973). A car fitted with instruments accompanied pedestrian survey teams to record wind speed, wind direction, air temperature, noise level, and solar radiation intensity at each location at the time of the surveys. During the same period another survey was conducted of people's preferences for city parks and plazas occupied during lunch hour. Similarly detailed recent studies of environmental conditions in urban street canyons have been conducted in Japan.

Field studies of wind effects provide useful information on existing conditions, to explore and compare wind conditions in a variety of urban design options (Aynsley 2001).

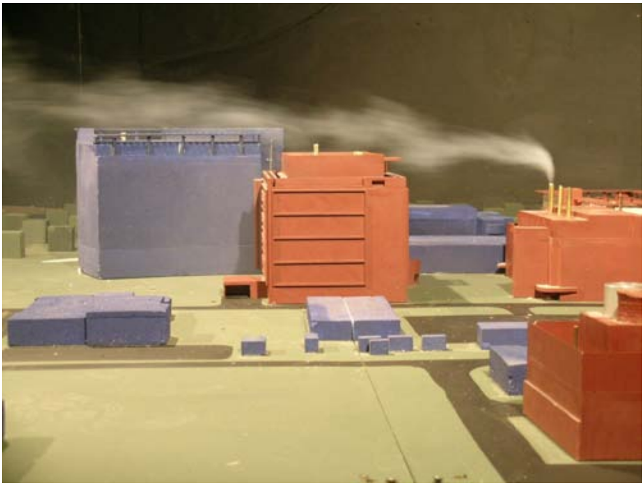


Figure 31. Urban air flow visualization using smoke (Courtesy of Cermak Peterka Petersen (CPP) Inc.).

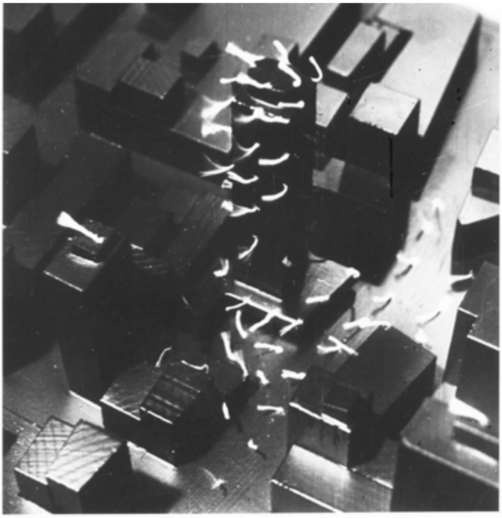


Figure 32. Urban flow visualization using tufts (Aynsley et al. 1997, with permission of Elsevier).

Figure 33. Urban flow visualization with foam plastic beads (Courtesy of Richard Aynsley).

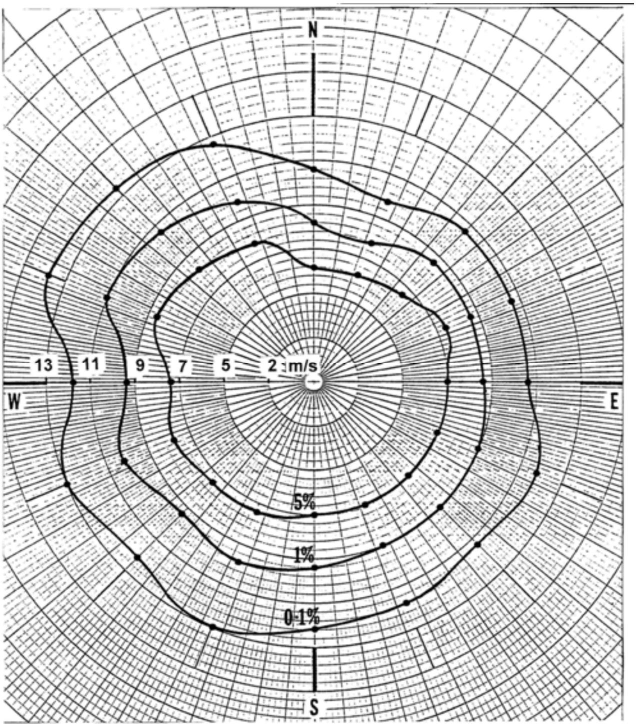


Figure 34. A polar plot of probability of occurrence, as a percentage of time of summer wind speeds from all directions at Hartsfield, Atlanta, GA, USA (Courtesy of Richard Aynsley).

Figure 35. An Urban Model inside a Boundary Layer Wind Tunnel (Courtesy of Boundary Layer Wind tunnel Laboratory, University of Western Ontario).

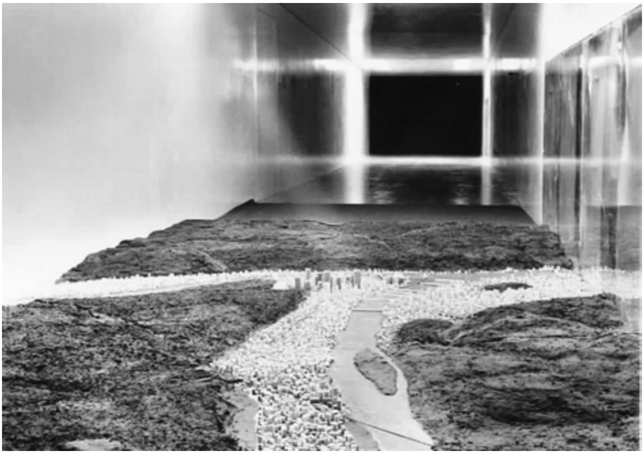


Figure 36. A 1:2000 model in the University of Western Ontario boundary layer wind tunnel for study of winds over the complex terrain (Davenport and Isyumov 1967, with permission of Boundary Layer Wind tunnel Laboratory, University of Western Ontario).

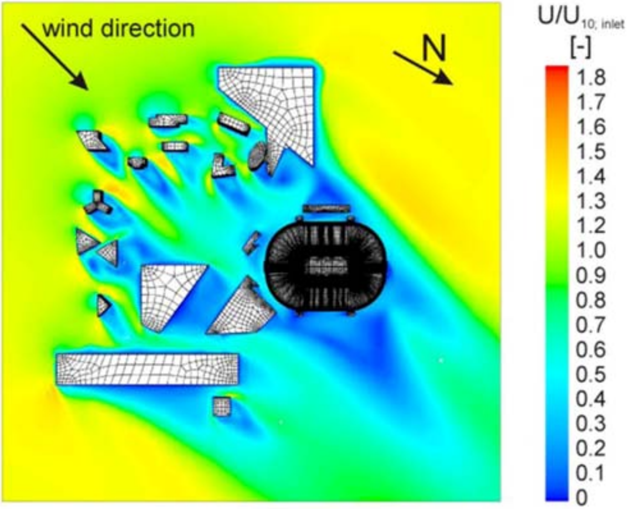


Figure 37. Contours of non-dimensional wind speeds U/U_{10} at 10m above the stadium ArenA deck and its surrounding buildings for an oblique wind direction and U_{10}=5 m/s (van Hooff and Blocken 2010, with permission of Elsevier).

CHAPTER 5

CONCLUDING REMARKS

At the Twelfth World Meteorological Congress in 1995 (WMC 1995), it was observed that almost half of the global population inhabit urban centers. A similar international conference on Biometeorology and Urban Climatology, was held in Sydney, Australia in 1999 (ICUC 1999).

Topics discussed at these conferences include:

- Pedestrian comfort
- Mitigation of airborne pollution from traffic and industry
- Mitigation of urban heat island effects by breeze penetration
- Potential for urban energy generation from wind turbines

This has led to increased interest in the impact of urban microclimates including wind effects on urban planning and design, and promises expanding opportunities for collaboration between urban planners, designers, and wind engineers.

Urban planners and designers, prior to 1960, did consider the impacts of wind on urban development but in a non-quantitative manner. Modern wind engineering began around 1960 with the relaxation of building height restrictions in many urban areas that resulted in the construction of large numbers of tall buildings in urban centers around the world. With increased redevelopment in urban areas came regulations to counter airborne pollution from vehicles in deep street canyons and thermal comfort and safety from strong wind gusts at pedestrian level near some tall buildings. More recently the integration of wind turbines into tall office buildings has been explored.

Boundary layer wind tunnels became the major tool for studying urban aerodynamics. Field studies have confirmed the validity of these wind tunnel studies. Computational fluid dynamics became more common in wind engineering much later with the rapid increase in computing power of small computers. There is still a need for more field studies to validate output from CFD studies and build general confidence in the method. More recently urban planners and designers have begun to work with wind engineers in order to use quantitative wind data to inform urban planning and design.

The greatest potential for saving energy in urban environments comes from utilizing natural ventilation for indoor thermal comfort in warm-humid, winterless climate regions. Sadly, many current urban commercial and residential developments in these regions make no attempt to use natural ventilation, but rely solely on refrigerative air conditioning. One area often overlooked in natural ventilation design is consideration of the backup system of energy efficient fans to maintain air movement during periods of calm.

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