

# Chapter 6

## Pedestrian Wind Environment Around Tall Buildings

Ted Stathopoulos and Bert Blocken

**Abstract** Pedestrian-level wind conditions around tall buildings are described by examining the aerodynamics of the urban environment and the various wind comfort criteria established in the wind engineering field. Experimental and, possibly, computational assessment of pedestrian-level wind conditions in the urban environment are described in detail. Particular emphasis has been placed on the state of the art and the capabilities of Computational Wind Engineering to determine at least mean values of wind speeds in the vicinity of buildings in urban areas. An approach toward the establishment of an overall comfort index taking into account, in addition to wind speed, the temperature, and relative humidity in the urban area under consideration, is presented.

**Keywords** Building • CFD • Comfort • Environment • Pedestrian • Wind tunnel

### 6.1 Introduction

The quality of open urban spaces has received a lot of attention in recent years. There is a broad recognition that microclimatic conditions contribute to the quality of life in cities, both from the economic as well as from the social viewpoint. Consequently, universities and other research organizations, municipal and other government forms, as well as construction and architectural companies have expressed significant interest and allocated resources to examine microclimatic conditions, particularly the effect of wind, on the outdoor human comfort. This task is quite complex because, contrary to the more or less controllable indoor comfort conditions, outside human comfort in an urban climate is generally

---

T. Stathopoulos (✉)

Department of Building, Civil and Environmental Engineering, Concordia University,  
Montreal, QC H3G 1M8, Canada  
e-mail: [statho@bcee.concordia.ca](mailto:statho@bcee.concordia.ca)

B. Blocken

Department of the Built Environment, Eindhoven University of Technology, 5600 MB  
Eindhoven, The Netherlands

Department of Civil Engineering, Leuven University, 3001 Leuven, Belgium  
e-mail: [b.j.e.blocken@tue.nl](mailto:b.j.e.blocken@tue.nl); [bert.blocken@bwk.kuleuven.be](mailto:bert.blocken@bwk.kuleuven.be)

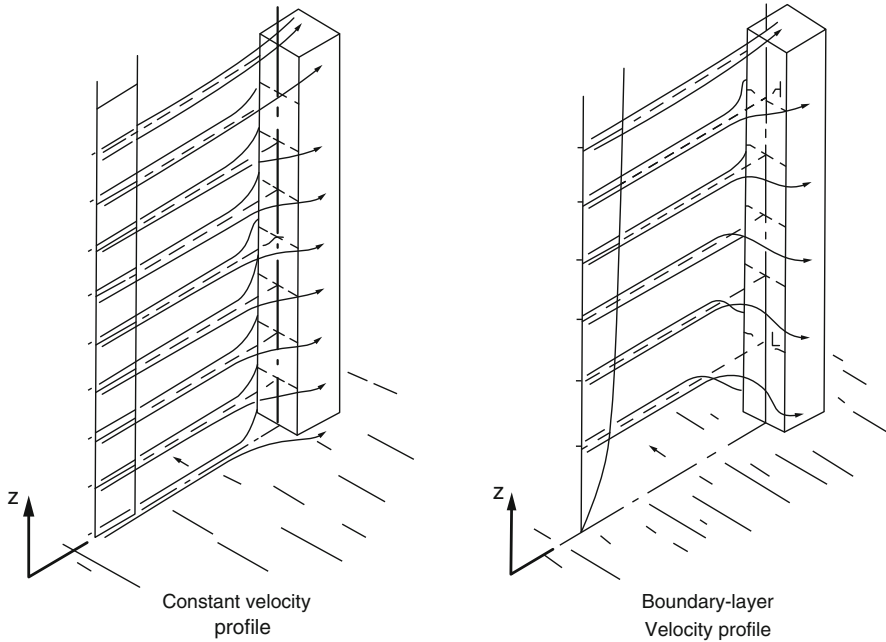
affected by a wide range of variables such as wind speed and direction, air temperature, solar radiation, possible precipitation in various forms, and the like.

In Europe, a 3-year (2001–2004) EU-funded project with extensive surveys carried out at different open spaces has carried out approximately 10,000 interviews (<http://alpha.cres.gr/ruros>). The project produced an urban design tool that provides architects, engineers, urban planners, and other decision-makers with means to assess effectively the construction of new buildings and the development of cities from the economic, psychophysiological, and sociological perspective of human comfort, air temperature, relative humidity, solar radiation, air quality, and human activity. Work has also been carried out within the auspices of the European Action C14 dealing with *Impact of Wind and Storm on City Life and Built Environment*, with a working group interested in the effects of wind on pedestrians, their assessment and comparisons, as well as the parameters that influence human comfort and its evaluation. Results have appeared in the 2002 Workshop in Nantes, e.g., Westbury et al. (2002) and in the International Conference in Urban Wind Engineering and Building Aerodynamics organized by the von Karman Institute for Fluid Dynamics in May 2004. In addition, the American Society of Civil Engineers (ASCE) has put out a pertinent state-of-the-art document (2003) which was developed with input from the European Action C14.

This chapter describes the aerodynamics of the urban environment and the reasons causing high wind speeds at sidewalks and, consequently, potential discomfort or danger to pedestrians, particularly in the proximity of tall buildings; it addresses the experimental and computational evaluations of the wind on people in the urban environment and focuses on the state of the art of the development of human outdoor comfort criteria by considering a wide range of parameters, including wind speed, air temperature, relative humidity, solar radiation, air quality, human activity, clothing level, age, and the like.

## 6.2 Aerodynamics of the Urban Environment

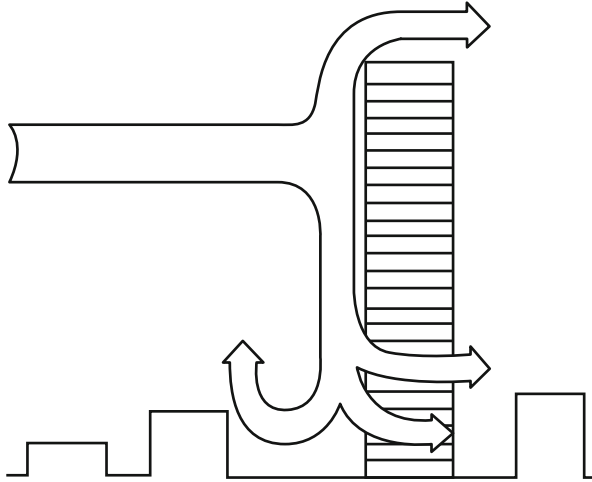
Strong winds are usually accelerated at the pedestrian level within the urban environment, say around tall buildings, due to particular aerodynamic configurations generally associated with tall buildings. In the case of a simple rectangular tall building, it is the boundary layer flow that causes descending flows toward the street level due to the pressure differences created by the velocity differences between higher and lower levels. This downflow is significant due to the pressure proportionality to the **square** of the velocity (Bernoulli equation) and the increase of the latter with the building height. Figure 6.1 demonstrates this effect, which is termed in the literature as *downwash*. Clearly, downwash is diminished drastically in the absence of boundary layer flow, and this explains the lack of adequate representation of wind effects in the building environment for simulations carried out in the past using aeronautical wind tunnels for building aerodynamics applications.



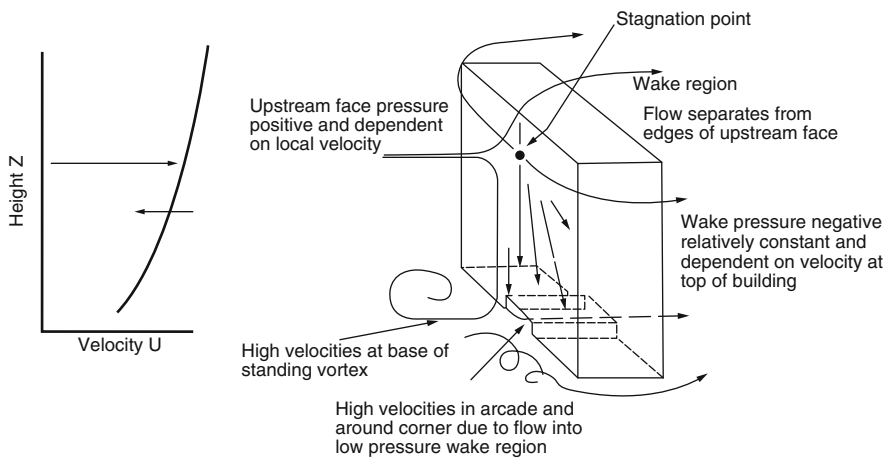
**Fig. 6.1** Uniform and boundary layer wind flow around a tall rectangular building

In general, buildings will only induce high wind speeds at lower levels if a significant part of them is exposed to direct wind flows. It is actually the direct exposure to wind rather than building height alone which causes the problem. This is shown diagrammatically in Fig. 6.2. Another type of pedestrian-level winds is formed when high-speed winds pass through openings between high-pressure air on the windward wall and low-pressure regions on the leeward side of a building. Once more, the fair character of nature, which does not like pressure differences, prevails and strong flow is induced to correct the problem. Pedestrians in arcades of commercial buildings can testify regarding this situation, which is unpleasant to the store owners in these areas as well. Figure 6.3 shows this type of configuration along with other flow-induced mechanisms creating disturbances to the urban environment in the vicinity of buildings. These include but they are not limited to the effects of the large standing vortex in front of a building, the vortex flows generated after the flow separates and accelerates along the building front edges, and the wake-induced disturbances via the interaction of the flow coming from the building side faces and the recirculation flow regime created by the shear layer flow above the building. Clearly, wind direction is a significant factor here, in addition to the magnitude of the oncoming wind speed.

Additional common building configurations and potential influences on pedestrian-level winds are shown in Fig. 6.4 taken from Cochran (2004). These configurations include the effects of canopies, which may act as deterrents to the strong downflow prior to impacting on sidewalks or other pedestrian-free access

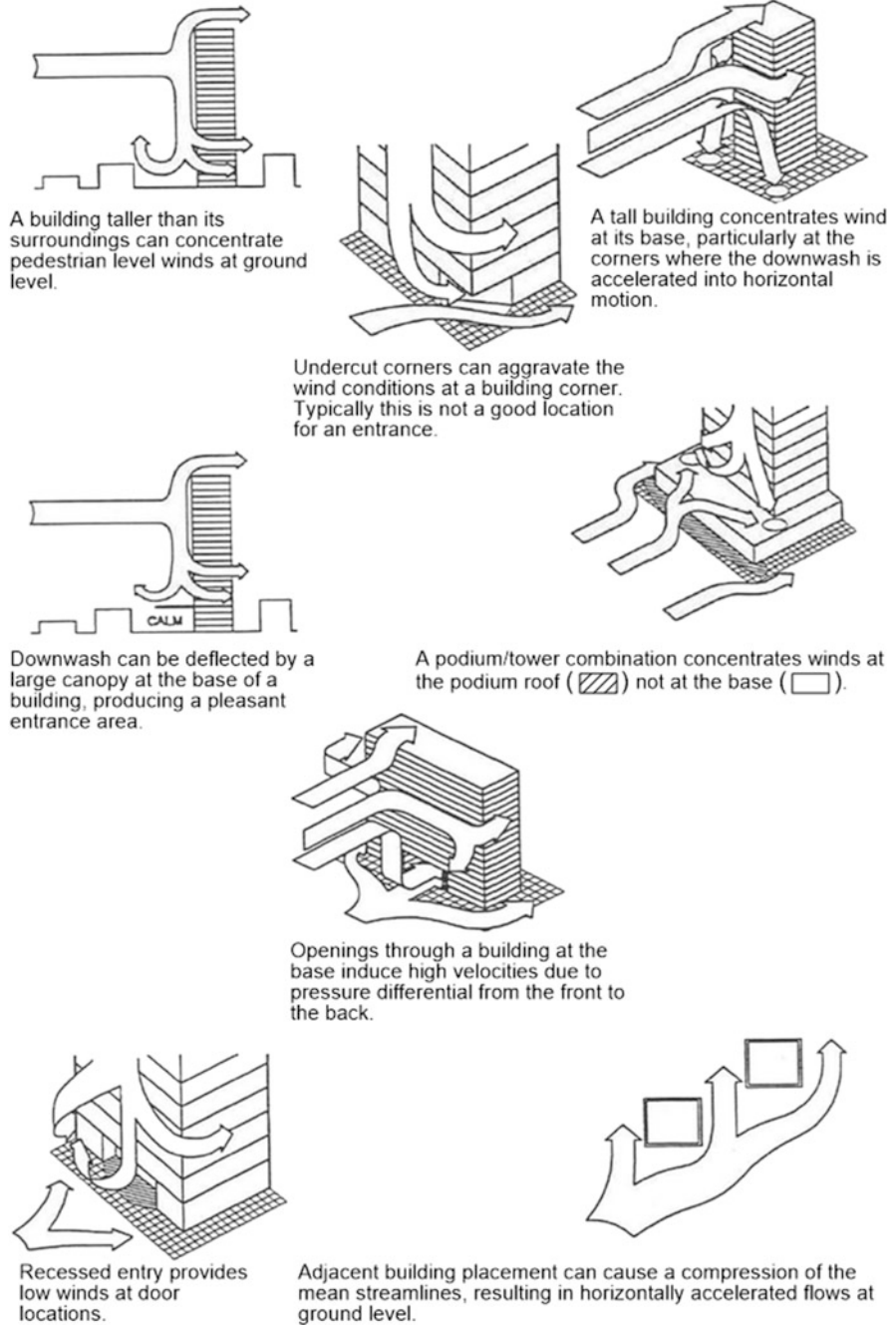


**Fig. 6.2** Wind flow around buildings significantly taller than their surroundings (After Cochran (2004))



**Fig. 6.3** Interaction of building with oncoming wind flow

areas around the building. However, such measures may create other problems by deflecting the wind from, say, a building entrance to another area around the building corners or across the street. Setbacks on the building surfaces or penthouses are elements generally remediating the pedestrian-level winds and are used rather extensively. Furthermore, a podium not intended for long-term pedestrian activities or vegetation in terms of bushes and coniferous-evergreen trees can also be used as a positive measure to amend harsh wind conditions at pedestrian level. Porous screens are also successful in deflecting winds without relocating the



**Fig. 6.4** Design features to change and/or ameliorate pedestrian wind conditions (After Cochran (2004))

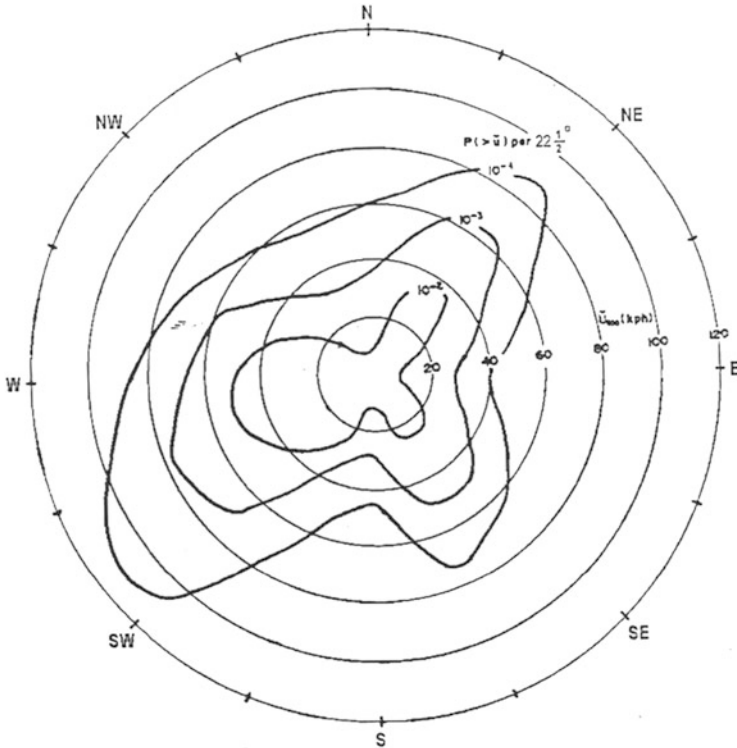
adverse conditions on other places. An entrance alcove, as well as balconies, also diminishes sidewalk winds in the cities. However, high winds may be transferring on balconies themselves, particularly those near the edges of the building facades.

The previous discussion is really about isolated and mainly rectangular buildings. Curved buildings such as cylindrical shapes generally promote lateral flow, so they behave better as far as effects of pedestrian-level winds are concerned. Channeling effects appearing in the case of two or more buildings are generally critical, particularly if the wind direction is along the street or corridor formed between the buildings. Previous computational and experimental research by Blocken et al. (2007, 2008a, b) indicated that the channeling effects are particularly pronounced in the passage near ground-level, while at higher positions in the passage, the flow speed actually reduces compared to free-field conditions. As a result, the overall flow rate through the passage decreases compared to open-field conditions, but the flow speed at pedestrian level increases. Based on these findings, Blocken et al. (2007, 2008b) preferred the term “channeling effect” to be used instead of Venturi effect, as the Venturi effect strictly only applies to confined flows (Venturi 1799), while atmospheric flows are open flows.

If the wind conditions with one or two simple-shaped buildings in place can become so complex, one can easily imagine what would really happen with buildings of complex shapes interacting with the wind flow passing among them, particularly when the effect of ground topography and all adjacent buildings is taken into account. The problem becomes really difficult and for a number of years could only be solved experimentally via appropriate simulation in a boundary layer wind tunnel. However, with the significant progress in computational technology, attempts were made to address the problem of pedestrian-level winds in the urban environment computationally. More detailed discussion on the state of the art of computational fluid dynamics (CFD) applied to – among others – the study of pedestrian-level winds can be found in the review papers by Stathopoulos (1997; 2002) and in the review paper by Blocken (2014) on 50 years of Computational Wind Engineering.

Regardless of the approach used to determine the impact of wind flows at the pedestrian level, the previous comments have demonstrated that the direction of the oncoming wind together with its magnitude, i.e., speed, will be of paramount importance. If the wind climate in a city is distinctly directional, i.e., strong winds come always from a particular narrow fetch, it is clear that this set of directions should be really scrutinized because, in all likelihood, critical results will occur when the wind comes from these particular directions.

As an example, the basic wind environment of Montreal in terms of wind speeds and probabilities of exceedance from different directions is presented in Fig. 6.5. As clearly shown, westerly and southwesterly winds dominate while north and north-easterly winds may also be high. Note that these are upper level winds and significant changes may occur near the ground areas. In addition, differences exist between summer and winter wind data. Maximum summer winds are dominant from west, while winter winds are certainly higher and they blow primarily from southwest. In the great majority of pedestrian wind studies carried out for tall buildings in Montreal, it has been found that winds from the west/southwest and, to



**Fig. 6.5** Probability distributions of hourly mean wind speed at 300 m overground for daylight hours during the winter (derived from 10-year record of wind data obtained at a height of 10 m at Montreal's Trudeau Airport)

a lesser extent from the northeast, have produced the most critical adverse conditions.

In summary, there are two main flow types causing high pedestrian-level winds in the urban environment: downwash flows and horizontally accelerated flows. The former are diminished by podia and architectural features such as setbacks, balconies, and the like; the latter are ameliorated by alcoves, chamfered corners, landscaping (vegetation), or porous screens.

### 6.3 Wind Comfort Criteria

Several criteria have been developed in the wind engineering community for evaluating only the wind-induced mechanical forces on the human body and the resulting pedestrian comfort and safety. There are significant differences among the criteria used by various countries and institutions to establish threshold values for

**Table 6.1** Extended land Beaufort scale showing wind effects on people (Lawson and Penwarden 1975; Isyumov and Davenport 1975)

Beaufort number	Description	Wind speed (m/s) at 1.75 m height	Effect
0	Calm	0.0–0.1	
1	Light air	0.2–1.0	No noticeable wind
2	Light breeze	1.1–2.3	Wind felt on face
3	Gentle breeze	2.4–3.8	Hair disturbed, clothing flaps, newspaper difficult to read
4	Moderate breeze	3.9–5.5	Raises dust and loose paper, hair disarranged
5	Fresh breeze	5.6–7.5	Force of wind felt on body, danger of stumbling when entering a windy zone
6	Strong breeze	7.6–9.7	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forward walking force, wind noise on ears unpleasant
7	Near gale	9.8–12.0	Inconvenience felt when walking
8	Gale	12.1–14.5	Generally impedes progress, great difficulty with balance in gusts
9	Strong gale	14.6–17.1	People blown over by gusts

tolerable and unacceptable wind conditions even if a single parameter, such as the wind speed, is used as a criterion. These differences range from the speed averaging period (mean or gust) and its probability of exceedance (frequency of occurrence) to the evaluation of its magnitude (experimental or computational).

Table 6.1 shows the traditional Beaufort scale used in ship navigation in a modified version applicable to land regions and for heights representative of pedestrians. This table provides an idea of the mechanical effects of wind of different speeds on the human body. Physiological effects are more complex since they depend on additional factors and their interactions.

A simple rule of thumb has been provided by Wise (1970) and Penwarden (1973). This is based on mean speeds ( $V$ ) assuming the following effects:

• $V = 5$ m/s or 18 km/h	Onset of discomfort
• $V = 10$ m/s or 36 km/h	Definitely unpleasant
• $V = 20$ m/s or 72 km/h	Dangerous

*Conditions for pedestrians are considered acceptable if  $V > 5$  m/s less than 20 % of the time (Penwarden and Wise 1975).*

Recognizing the importance of frequency of occurrence along with the magnitude of wind speeds, Figs. 6.6, 6.7, and 6.8 provide threshold mean wind speeds for various types of activity as functions of the average annual number of storm





**Fig. 6.6** Wind tunnel exposure of people at 10–15 km/h winds

occurrences. Naturally the mean wind speed threshold level drops significantly as the yearly average number of occurrences increases.

Wind tunnel experiments and observations of pedestrian performance suggest that  $\kappa = 3$  is the most appropriate value. Figure 6.9 shows acceptance criteria for wind speeds for various annual frequencies of occurrence proposed by Isyumov and Davenport (1975). Note that these criteria are different from previous criteria in that, instead of specifying a wind speed for various activities, frequencies of occurrence are specified for different wind speeds. Murakami et al. (1986) produced the wind comfort criteria described in Table 6.2.

Melbourne (1978) has produced separate criteria based on mean and gust speeds. He proposed their application only for daylight hours and on the assumption that the max 2-s gust speed will be roughly twice as large as the mean speed, he produced the curves shown in Fig. 6.10. These curves identify threshold wind speed criteria for different types of activity similar to those shown in Table 6.2. Criteria for dangerous wind conditions were also specified. Such conditions are particularly important for cities with harsh winter conditions where icy sidewalks become source of frequent accidents when combined with high winds. Several cases of this nature have been reported, most involving accidents happened on elderly people. Liability issues are also interesting for such cases and courts have always a hard time dealing with them.



**Fig. 6.7** Wind tunnel exposure of people at 20 (*left*) and 40 (*right*) km/h winds

On the basis of experience over a number of projects and wind tunnel studies, it has been concluded that Melbourne's criteria are on the strict side, i.e., if prevailing conditions abide by the prescribed limits, most sets of other criteria available in the literature or included in ordinances of various municipalities will be satisfied. Consequently, these criteria can be used as upper limits for pedestrian-level winds and, in this regard, are indeed valuable.

### **6.3.1 Wind Ordinances in Major Cities**

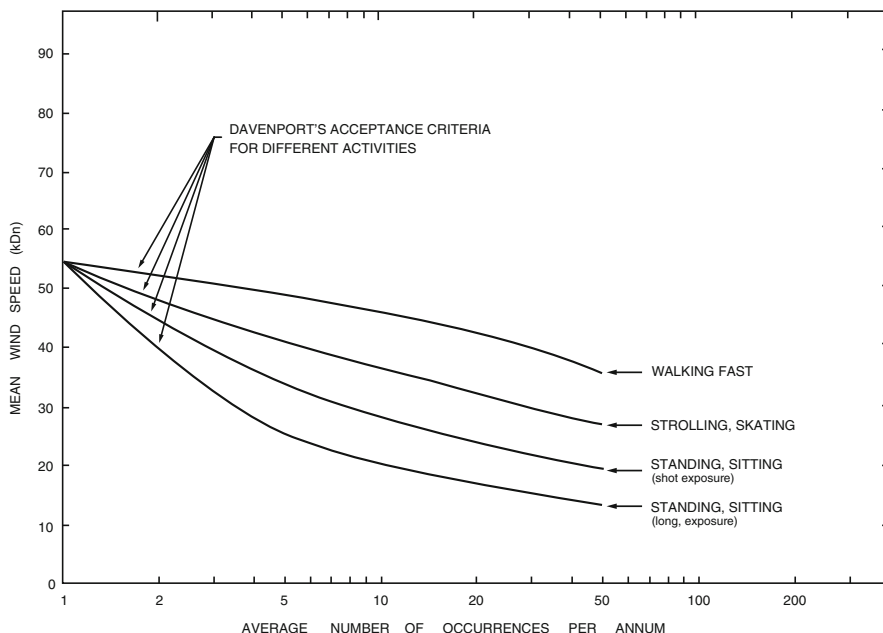
There is great variation regarding wind ordinances in various cities around the world. In some cases, specific legislation has passed, and new building permits are not provided until the developers/owners demonstrate that the project will not generate dangerous or even uncomfortable and undesirable pedestrian-level wind conditions. In other cases, this is expected to happen as part of assumed good engineering and architectural practice. In general, the following points can be made:



**Fig. 6.8** Wind tunnel exposure of people at 70 km/h winds

- Most major cities (Montreal, Toronto, Sydney, etc.) have some guidelines addressing the problem at the approval stage for new construction projects.
- San Francisco has adopted a very strict wind ordinance; they use  $v^e = 42$  km/h with  $P(>V^e) = 0.01\%$  as safety criterion; this is significantly lower than that proposed in most of the current literature.
- New York has strict air pollution standards, which tend to work against guidelines for the pedestrian wind environment; only 30% of new developments have to go through a review process.
- The Boston Planning Department specifies that a wind tunnel study is required to assess wind environmental conditions near new developments for the following cases:
  - (i) For any new building taller than 30 m (100 ft) and at least two times taller than its adjacent buildings
  - (ii) For other buildings in special circumstances

As it is always the case with any adoption of code provisions or changes, passing legislation regarding pedestrian wind conditions is always problematic. It is worth mentioning that after several years of intense efforts by several experts, architects and engineers, a new wind ordinance has been approved in the Netherlands. It

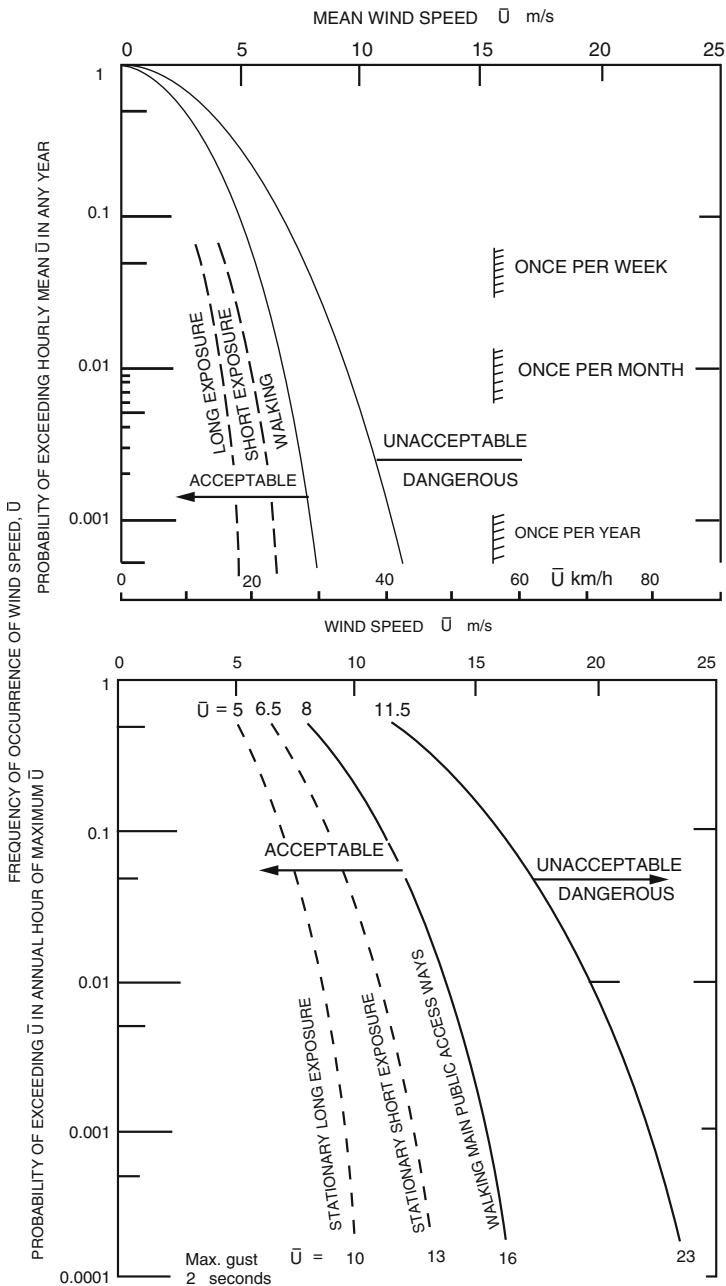


**Fig. 6.9** Acceptance criteria for wind speeds for various annual frequencies of occurrence (After Isyumov and Davenport (1975))

**Table 6.2** Wind environment criteria of Murakami et al. (1986)

Activity	Probability of $\dot{u} = 36$ kph	Exceedance $\dot{u} = 54$ kph	(P(>u)) $\dot{u} = 72$ kph
Long-term and short-term stationary exposure	0.10	0.008	0.0008
Strolling	0.22	0.036	0.006
Walking	0.35	0.07	0.015

represents the first standard on wind nuisance and wind danger in the world (NEN 2006a, b), and it is based on research by Verkaik (2000, 2006), Willemsen and Wisse (2002, 2007), Wisse and Willemsen (2003), and Wisse et al. (2007), among others. It was incited by the wide range in procedures and criteria being used by universities, research institutes, and consultancy companies across the country, sometimes yielding very different outcomes for the same building or urban area. In particular, the standard presents a uniform approach for each of the three main components of a wind comfort or wind danger study: the statistical meteorological data (including exposure corrections), the transformation of these data to the building site, and the comfort and danger criteria. A remarkable feature of the standard is that it explicitly allows the user to choose between wind tunnel modeling and CFD to determine the design-related contribution, as part of the transformation of wind statistics to the building site. Case studies applying this new



**Fig. 6.10** Probability distributions of Melbourne’s criteria for environmental wind conditions for daylight hours for a turbulence intensity of 30 % and  $\hat{u} = 2u$  (After Melbourne (1978))

standard for different urban areas can be found in Blocken and Persoon (2009), Blocken et al. (2012), Janssen et al. (2013), and Montazeri et al. (2013).

## 6.4 Experimental Procedure: Wind Tunnel Approach

### 6.4.1 General

The testing of scale models in a boundary layer wind tunnel capable of simulating the mean velocity profile and turbulence, as well as the spectra of the natural wind, has been shown to be a very effective method of prediction by comparison with respective full-scale data. The wind tunnel model typically includes all buildings in the surrounding landscape; thus, their effect is automatically included. Both existing conditions and those with the new building(s) in place can be readily measured, thus allowing the impact of the new building(s) to be identified. Furthermore, the effects of changes to the building itself, or to landscaping, can also be studied, particularly where undesirable wind conditions are found.

A typical setup of a wind tunnel model in a boundary-layer wind tunnel is illustrated in Fig. 6.11. The building itself and the model of its surroundings are mounted on the wind tunnel turntable, which can be rotated to allow various wind directions to be simulated. Typical model scales for large buildings are in the range from 1:200 to 1:500. Larger scales have been used for smaller buildings. The model of surroundings enables the complex flows created by other buildings near the study



**Fig. 6.11** Typical wind tunnel setup for a pedestrian wind assessment study in the atmospheric boundary layer wind tunnel at Concordia University, Montreal

building to be automatically included in the tests. However, it is also essential to create a proper simulation of the natural wind approaching the modeled area. The requirements for modeling the natural wind in a wind tunnel are described in the ASCE Manual of Practice (1999), as well as in the ASCE Standard 49-12, ASCE (2012). In typical wind tunnel tests, the airflow speed above the boundary layer is in the range 10–30 m/s. The process followed in the experimental approach consists of the following steps:

1. Meteorological records
2. Wind tunnel testing
3. Combination of (1) and (2)
4. Comparison with comfort criteria
5. Remedial measures

Details of this process will be presented in the following case study.

### 6.4.2 Case Study

This is an actual study in Montreal, but names have been withheld and sample results presented are also coming from another unnamed study for reasons of confidentiality. The study was conducted in the Building Aerodynamics Laboratory of Concordia University using a 1:500 model of the buildings and their surroundings. Wind environmental conditions at the sidewalks around the new buildings were assessed in terms of peak (gust) and mean speeds. The following configurations were considered in the study:

1. Present conditions
2. Proposed development

The architects of the project provided the details of the design, and the building models were placed on a maquette with the surroundings on a full-scale equivalent radius of 300 m. Environmental wind conditions on sidewalks around the building were assessed for the critical southwesterly and northeasterly wind directions – see Fig. 6.5. Measurements were obtained at the locations shown in Figs. 6.12 and 6.13. The 1:500-scaled model of the proposed development and the surroundings was mounted on the turntable of the boundary layer wind tunnel. Wind velocities were measured at 31 ground-level locations, but results for only six points are shown herein. Five of the sampling points (3, 5, 6, 7, and 8) were located on S street and one point (15) was located in the courtyard.

Pedestrian wind data were obtained with a hot film sensor located at a full-scale equivalent height of 2 m above the ground. The reference mean velocity in the wind tunnel at a full-scale equivalent height of 300 m,  $U_{300}$ , was also measured. The ratio  $\hat{U}_{local}/U_{300}$  was determined for each wind direction, where  $\hat{U}_{local}$  is the gust velocity at ground level. The test results were then combined with meteorological data

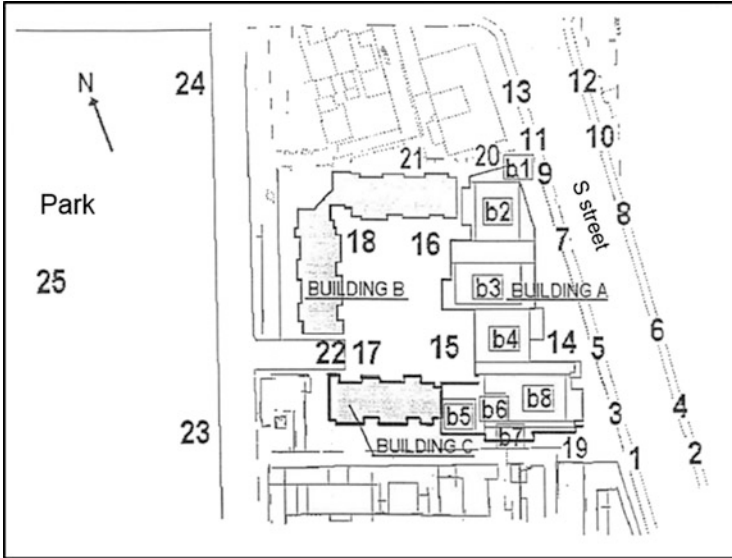


Fig. 6.12 Plan view of proposed development showing measurement locations

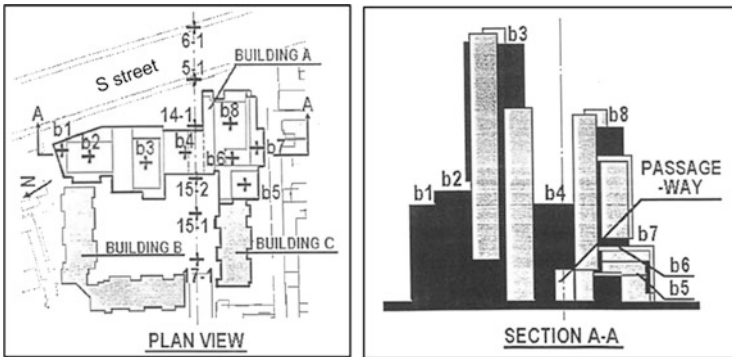


Fig. 6.13 Plan and elevation view of proposed development showing measurement locations near and on buildings

recorded at the P.E. Trudeau (Dorval) International Airport for a 10-year period in order to predict wind speeds with a particular return period for each test location. The Trudeau data, consisting of mean hourly wind speeds obtained in open country terrain at a height of 10 m, have been used to derive probability distributions of wind speed and direction for Montreal. These wind speeds were adjusted to an urban exposure at a height of 300 m using the following formulas:



$$U_{300, \text{open country}} = U_{10, \text{Dorval}} \left( \frac{300}{10} \right)^{0.15}$$

and

$$U_{300, \text{urban}} = U_{300, \text{open country}} \left( \frac{300}{450} \right)^{0.34}$$

since  $U_{450, \text{urban}} = U_{300, \text{open country}}$ . Note that the exposure category characterizes the terrain several kilometers upwind of the site.

Probability distributions of wind speed and direction for a suburban exposure at a height of 300 m similar to that presented in Fig. 6.5 have been evaluated for summer and winter, respectively. These distributions, which are based on data for daylight hours (07:00–19:00), indicate that strong winds occur most often from W, WSW, and SW directions and occur more frequently during the winter than in the summer. Data also show that the probability of strong winds from the NE is relatively high. The probability of exceedance [ $P(>)$ ] corresponding to once per month and once per year are approximately  $10^{-2}$  and  $10^{-3}$ , respectively. For instance, a westerly wind at a height of 300 m is expected to exceed 48 kph approximately once per month during the winter. Although the proposed development will be highly exposed to winds from the east quadrant, the probability of strong winds from the east is relatively low. It should be noted that the influence of Mount Royal on Montreal’s wind climate is not evident in the meteorological data used, since the probability curves were derived from data obtained at Trudeau (Dorval) Airport. It is anticipated that the presence of Mount Royal should reduce the probability of strong winds at the site for westerly and southwesterly winds. Therefore, the results presented in this study are expected to be generally conservative.

Melbourne’s criteria shown in Table 6.3 have been used for the characterization of wind comfort conditions at the pedestrian level. The peak wind speed acceptable for walking was reduced to 32 kph for the winter months to take into account the effect of temperature on pedestrian comfort. As suggested in ASCE (2004), the summer wind speed should be reduced by one Beaufort number for every 20 °C reduction in temperature. The second criterion indicates that wind conditions are hazardous if the gust velocity exceeds 83 kph more than once per year. At this wind speed, people can be blown over.

**Table 6.3** Melbourne’s pedestrian comfort criteria (Melbourne 1978)

Wind condition	$\hat{U}_{local}$	$P(>\hat{U}_{local})$
Acceptable for walking		
Summer	48 kph	0.01 (once per month)
Winter	32 kph	0.01 (once per month)
Hazardous	83 kph	0.001 (once per year)

### 6.4.3 Sample Test Results

Data obtained under the current conditions and with the proposed development are plotted in polar form in Fig. 6.14 for a typical set of four measurement points. As suggested in Westbury et al. (2002), the data are plotted in terms of the velocity pressure ratio  $(\dot{U}_{local}/U_{300})^2$ . Melbourne's wind environment criteria for winter conditions have been included on the diagrams, in terms of curves determined by incorporating the probability distributions shown in Fig. 6.10. These curves show the limiting wind pressure values for walking comfort and for extreme hazard.

Figure 6.14 shows whether the proposed development does adversely affect the wind climate at different locations. For instance, the building causes an increase in gust speed at locations 6 and 8 for westerly and southwesterly winds and at location 6 for northeasterly winds. For these cases, Melbourne's comfort criteria were exceeded. However, it should be noted that the proposed development will improve wind conditions at all points for at least some wind directions. It can also be noted that at location 7, wind conditions were improved for all of the tested wind directions. The results of the study indicate that the proposed buildings will have relatively little adverse effect on the pedestrian wind environment. Winter winds, which are presented in Table 6.3, are more critical than those occurring during the summer. For the proposed development, the maximum wind gust expected to occur once per month in the winter is approximately 43 kph. Under current conditions (i.e., without the new building), the peak monthly gusts in the winter are approximately 33 kph at the same location.

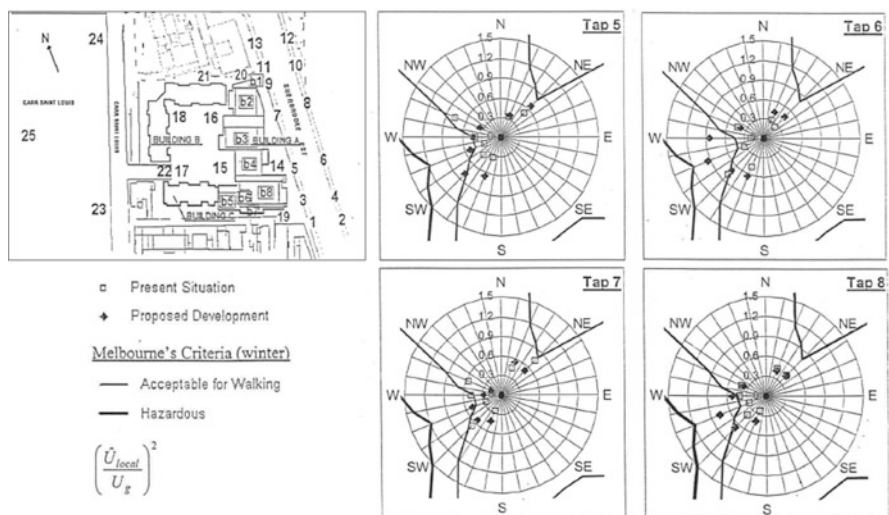


Fig. 6.14 Measurement of velocity pressure ratio at locations 5, 6, 7, and 8

#### 6.4.4 Comparison with Montreal's Wind Criteria

The city's wind comfort criteria, specified in Article 39 of the *Règlements refondus de la ville de Montréal*, refer to mean wind speeds rather than gust speeds. The critical mean wind speeds,  $U_{local}$ , for winter and summer are 14.4 kph (4 m/s) and 21.6 kph (6 m/s), respectively, and the maximum acceptable probabilities of exceeding these values are as follows:

Location	Probability of exceedance of $U_{local}$
Main streets	15 %
Secondary streets	25 %
Parks	10 %

As previously mentioned, the wind tunnel data are expressed in terms of the local peak velocity pressure ratio, which is given as  $(\hat{U}_{local}/U_{300})^2$ , where  $\hat{U}_{local}$  is the local gust velocity and  $U_{300}$  is the mean wind speed measured at the reference full-scale height of 300 m for an urban exposure. Using these data, the local mean velocity pressure ratio  $(U_{local}/U_{300})^2$  is obtained by assuming that the peak velocity is two times the mean value,  $U_{local}$  (see Art. 38.5). Given the probability of exceedance of  $U_{300}$ , the probability of exceedance of any local mean wind speed – in this case, 14.4 kph (4 m/s) for winter conditions – can be determined for each wind direction. The total probability of exceedance is obtained by simply adding the probabilities determined for each wind direction.

For example, the gust velocity pressure ratio obtained at the assumed windiest location 6 with the proposed development for a west-southwesterly wind is 0.935 (see Fig. 6.14). Taking the square root and dividing by 2 gives the local mean velocity ratio of  $U_{local}/U_{300} = 0.48$ . Setting  $U_{local}$  equal to 14.4 kph gives the critical reference velocity of  $U_{300} = 30$  kph for this wind direction. Based on wind speed data from Trudeau (Dorval) Airport, the probability of exceedance of this wind speed during daylight hours (07:00–19:00) in the winter months (November–April) is approximately 0.036 (3.6 %). Following this procedure for the other tested wind directions gives a total probability of occurrence of 0.0837 (8.37 %). For the wind directions not tested, the probability of  $U_{local} > 14.4$  kph is expected to be very small – of the order of 1 %. Thus, the total probability of  $U_{local} > 14.4$  kph at location 6 is approximately 9.37 %, as shown in Table 6.4. Consequently, the Montreal winter criterion for wind comfort on main streets ( $U_{local} > 14.4$  kph less than 15 % of the time) is satisfied at location 6.

Furthermore, since location 6 is the windiest point in the project area, the Montreal standard is satisfied at all other locations and for all configurations tested in the study. This includes locations in an adjacent park, tested previously, even though the criterion is stricter for park areas ( $U_{local} > 14.4$  kph less than 10 % of the time).

**Table 6.4** Comparison with Montreal's wind criteria

Wind direction	$(\hat{U}_{local}/U_{300})^2$	$\hat{U}_{local}/U_{300}$	$U_{local}/U_{300}$	$U_{300}$ (kph) at $U_{local} = 14.4$ kph	Probability $U_{local} > 14.4$ kph
NNE	0.421	0.649	0.32	45.0	0.0016
NE	0.456	0.675	0.34	42.4	0.0040
SSW	0.643	0.802	0.40	36.0	0.0008
SW	0.701	0.837	0.42	34.3	0.00095
WSW	0.935	0.967	0.48	30.0	0.0360
W	0.834	0.913	0.46	31.3	0.0300
WNW	0.381	0.617	0.31	46.3	0.0018
Other directions					0.0100
				<b>Total</b>	<b>0.0937</b>

Expected probabilities of exceeding the Montreal winter criterion ( $U_{local} > 14.4$  kph) at location 6 due to the proposed development

The preceding example illustrates that strong winds at ground level are not likely to occur for a given wind direction unless  $(\hat{U}_{local}/U_{300})^2$  is large, and the probability of strong winds from that direction is also large. Regarding the wind comfort criterion for the summer months, analysis of the data shows that the criterion will also be met at all locations. Due to the larger acceptable wind speed (21.6 kph) and the reduction in the frequency of high winds for the summer months, the probability of exceeding the summer criterion is less than that for the winter criterion at each location.

With respect to the city's criteria concerning hazardous wind conditions (*Art. 40, Règlements refondus de la ville de Montréal*), the wind conditions around the proposed development were found to be acceptable. The wind tunnel results show that predicted gust speeds with a probability of exceedance of 0.01 (once per month) are well below the criterion of 72 kph (20 m/s) at all measurement locations. For all design options, the maximum monthly gust in the winter is expected to be approximately 43 kph at locations 6 (on S street) and 15 (on passageway). Finally, it should be recalled that the anticipated wind speeds are based on statistical expectations and actual wind conditions during a particular storm may be different. Future building developments in the surrounding area may also affect the pedestrian wind environment, but this has not been considered in the present study.

## 6.5 Computational Procedure: CWE

In Computational Wind Engineering (CWE), the computer simulation essentially replaces the physical simulation in the boundary layer wind tunnel, at least in principle. Computational fluid dynamics (CFD) methods involve very large amounts of computation even for relatively simple problems, and their accuracy is often difficult to assess when applied to a new problem where prior experimental

verification has not been done. Castro and Graham (1999), Stathopoulos (1997; 2002) and Blocken (2014) summarized the concerns expressed with respect to these issues. However, there have been cases for which the application of CFD methodologies appears to give somewhat satisfactory responses. These are cases requiring the determination of mean flow conditions and pressures, i.e., those related primarily with environmental issues. Typical problems of this category include but are not limited to pedestrian-level winds, snow dispersion and accumulation, dispersion of pollutants in the near-building and/or urban environment, ventilation, and the like. There is increasing evidence that for such problems CFD-based techniques may provide adequate responses – see Stathopoulos (2002) and Blocken (2014).

Pedestrian-level winds can be described quite adequately in terms of mean velocities in the presence and absence of a new building within a specific urban environment. Although it can be argued that pedestrians are mostly affected by gust effects and mean wind speeds may not be sufficient to produce satisfactory results, the fact remains that several major cities require only the satisfaction of certain mean (sustainable) speeds with a specified probability of exceedance. A number of computational studies for the evaluation of pedestrian-level winds and the comparison of their results with respective experimental data are encouraging. The process of comparison between computational and experimental results has already been challenged and appears problematic on its own. For instance, is it more meaningful to carry out point-by-point comparisons or does it make more sense to examine pedestrian-level wind speeds affecting a particular zone or area of influence for a specific activity within the urban environment? Furthermore, and after due consideration to the fact that pedestrian-level wind speeds measured in the proximity of buildings, i.e., in areas of high turbulence, are not very accurate, it may be conceivable that “errors” in the results might be better described in terms of their impact on design decisions. Clearly, this may be more reasonable, at least in the context of engineering perspective.

### **6.5.1 Case Studies**

Bottema (1993) has attempted the evaluation of pedestrian-level wind conditions in the vicinity of an isolated building by using the CWE approach and a simple turbulence model but with only limited success. Studies published by Stathopoulos and Baskaran (1996) have demonstrated that by using a simple version of  $k-\epsilon$  model, one may obtain computational results very comparable with corresponding values originating from respective wind tunnel studies. The comparison of computed and measured velocity ratios at 2 m above the ground level in the presence and absence of a proposed building is generally satisfactory with a maximum discrepancy of the order of 30 %. It is noteworthy that the maximum discrepancies between the experimental and numerical data appear in highly complex recirculating flow regions, for which neither the measured nor the computed values can be considered very accurate.

This type of data response has been found and confirmed by several authors. For instance, Timofeyef (1998) evaluated the wind flow around a five-storey-high development in Kazakhstan and produced full-scale results, wind tunnel data, and numerical results by using the discrete vortex method (two-dimensional flow). Surprisingly enough, computational results compare better with corresponding full-scale data than the latter with wind tunnel results. This means that this rather crude computational approach provides more representative results than wind tunnel testing, at least in this particular case. In a cooperative study between Portugal and Canada, Ferreira et al. (1999) produced wind flow around a group of low-rise buildings (Expo' 98 – Lisbon). Both wind tunnel and field data were compared with numerical results obtained with the standard formulation and the renormalization group (RNG) extension of the  $k$ - $\epsilon$  turbulence model. By and large the comparisons are satisfactory, at least for engineering design purposes.

Hu and Wang (2002) have also attempted the evaluation of street-level winds in a built-up area by using CFD. Computational velocity ratios obtained through the commercially available code “PHOENICS” agree reasonably well with the experimental results for surrounding blocks of similar height. However, the comparison results deteriorate when the surrounding blocks consist of buildings with different heights. Such trends are possibly due to the more significant interaction of horizontal separated flow with the downflow originating from the pressure difference at different heights.

Wind tunnel and CFD data have been compared for a complex development in central London, which includes a 40 m high apartment block adjacent to an 80 m tower block, and a number of other buildings – see Miles and Westbury (2002). This study forms part of a research program at BRE, which aims to assess whether CFD is “fit for purpose” for use during the design process and to determine the major sources of inaccuracy associated with user modeling decisions. The inlet mean velocity profile measured in the wind tunnel, representing an urban boundary layer, has been used in the CFD simulation. Turbulence kinetic energy and dissipation rate profiles have been derived using boundary layer parameters obtained from fitting the logarithmic law to the measured velocity profile, combined with expressions from Richards and Hoxey (1992). Wall boundary conditions were defined using a rough-wall turbulent wall function applied at the ground, and a smooth-wall function applied to the building envelopes. A number of turbulence models have been tested – see details in Westbury et al. (2002).

Finally, it is worth mentioning an intensive Japanese effort to compare CWE results in terms of pedestrian-level wind speeds with respective experimentally measured values in an actual environment – see Tominaga et al. (2004). The correspondence between the CFD and the experimental results is fairly good with the exception of the wake region.

## 6.6 Outdoor Comfort Issues

Outdoor human comfort in an urban climate depends on a wide range of weather and human factors. Studies have shown integrated effects of wind speed, air temperature, relative humidity, and solar radiation on the human perception, preference, and overall comfort in an urban environment. Some analysis of these issues has been presented in the ASCE SOA Report, ASCE (2004). Furthermore, the studies by Nicolopoulou et al. (2001) and Nicolopoulou and Lykoudis (2002) also address the influence of microclimatic characteristics in outdoor urban spaces and the comfort implications for the people using them. A significant characteristic is the psychological adaptation, which has also been addressed. An equivalent temperature has been defined and related to the outdoor human comfort by considering acclimatization and other biometeorological principles (Stathopoulos et al. 2004; Zacharias et al. 2001). However, the implications of this approach are far fetching and the overall assessment problems are still quite intriguing. Some basic ideas are presented here.

### 6.6.1 *Temperature and Relative Humidity*

Both can have a significant impact on a person's comfort, since sensation of comfort in cold conditions is linked to the heat balance of the human body, i.e., the balance of heat generated by metabolic processes and heat lost by conduction, convection, radiation, and evaporation. In convective and evaporative losses, the effects of temperature and humidity are closely linked with the wind conditions and cannot be treated in isolation from wind speed. This is why, for example, in the colder regions of Europe and North America, the wind chill equivalent temperature is used to provide a more meaningful description of how cold weather will really feel, rather than simply giving air temperature. The equivalent temperature is obtained by calculating the temperature in standard wind (set at  $1.8 \text{ m/s} = 4 \text{ mph}$ ) that would give the same rate of heat loss from the exposed skin at  $33^\circ\text{C}$  as occurs in the actual wind and temperature conditions. Generally, in cold conditions, humidity is low and has little direct effect on thermal comfort, although there may be indirect effects, such as humidity changing the insulation value of clothing. In hot conditions, the human body needs to increase heat losses to maintain thermal comfort. This is largely achieved by reducing clothing and through sweating and the corresponding heat losses associated with the latent heat of evaporation. Since the efficiency of evaporation is decreased as the relative humidity of the air increases, the relative humidity becomes a much more important parameter in hot climates. Also, since the efficiency of evaporation is increased with wind speed, in cold climates it is often desirable to reduce wind speeds, but the opposite is sometimes the case in hot climates. The well-known humidex is an effective temperature, combining the temperature and humidity into one number to reflect

the perceived temperature and to quantify human discomfort due to excessive heat and humidity. In general, almost everyone will feel uncomfortable when the humidex ranges from 40 to 45, and many types of labor must be restricted when the humidex is 46 and higher. The incorporation of relative humidity effects into the overall assessment of thermal comfort is discussed in Stathopoulos et al. (2004).

### 6.6.2 *Solar Radiation*

Any assessment of thermal comfort must account for the effects of sun/shade conditions. The angle of the sun, the amount of radiation absorbed by clouds, dust and particles in the atmosphere, and the sunlight absorbed and reflected by buildings need to be taken into account.

### 6.6.3 *Precipitation*

In heavy rain conditions, people are less likely to be outside, thus their wind and thermal comfort will usually be less critical compared with other microclimate factors. However, it may be of interest to evaluate how far under a sheltering canopy roof the precipitation will infiltrate and how often this will happen. Dampness of clothes may also be of interest because it will affect thermal comfort.

A working group of the International Society of Biometeorology has developed a new standardized universal thermal climate index (UTCI), which can also be used in the development of a criterion for human outdoor comfort (Hoppe 2002). An example of application of such an approach is shown in Stathopoulos et al. (2004). The dependence of the overall comfort is expressed on the basis of a group of survey respondents as a function of the difference of two equivalent temperatures: one based on the weather norm,  $T_{e,n}$ , and the other based on the actual outdoor conditions,  $T_{e,a}$ . Equivalent temperatures take into account the effect of relative humidity and solar radiation as well. It should be noted that  $(T_{e,a} - T_{e,n})$  is the most influential factor on the overall comfort of the respondents. The study shows that (1) most comfortable conditions occur when the equivalent temperature difference is about 5 °C, which may be attributed to the preference of local residents for higher air temperature, as well as the temperature difference between an urban environment downtown and the airport; (2) lower comfort occurs with a negative temperature difference, or when the actual equivalent temperature is lower than the norm; and (3) if the temperature difference is beyond a certain limit, say greater than 10 °C, less comfortable (overall comfort < 1) outdoor conditions may be perceived, although more field data are necessary to confirm this observation. At present, it is still considered premature to draw a curve for a definite mathematical relationship of overall comfort and equivalent temperature difference.



## 6.7 Concluding Remarks

This chapter has dealt with pedestrian-level wind conditions, their origin, their experimental and, possibly, computational assessment in the urban environment, as well as with the criteria used for outside human comfort. Particular emphasis has been placed on the state of the art and the capabilities of Computational Wind Engineering to determine at least mean values of wind speeds in the vicinity of buildings in urban areas. An approach toward the establishment of an overall comfort index taking into account, in addition to wind speed, the temperature, and relative humidity in the urban area under consideration, was presented.

**Acknowledgment** The assistance of several graduate students in putting this chapter together and the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) to the first author are gratefully acknowledged and highly appreciated.

## References

- ASCE (1999) Manual of practice No. 67 on wind tunnel studies of buildings and other structures. ASCE, Reston
- ASCE (2004) Aerodynamics Committee, outdoor human comfort and its assessment, state of the art report. Task Committee on Outdoor Human Comfort, American Society of Civil Engineers, Reston
- ASCE (2012) Wind tunnel testing for buildings and other structures, ASCE standard 49–12. American Society of Civil Engineers, Reston
- Blocken B (2014) 50 years of computational wind engineering: past, present and future. *J Wind Eng Ind Aerodyn* 129:69–102
- Blocken B, Persoon J (2009) Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard. *J Wind Eng Ind Aerodyn* 97(5–6):255–270
- Blocken B, Carmeliet J, Stathopoulos T (2007) CFD evaluation of wind speed conditions in passages between parallel buildings – effect of wall-function roughness modifications for the atmospheric boundary layer flow. *J Wind Eng Ind Aerodyn* 95(9–11):941–962
- Blocken B, Stathopoulos T, Carmeliet J (2008a) Wind environmental conditions in passages between two long narrow perpendicular buildings. *J Aerosp Eng, ASCE* 21(4):280–287
- Blocken B, Moonen P, Stathopoulos T, Carmeliet J (2008b) A numerical study on the existence of the Venturi-effect in passages between perpendicular buildings. *J Eng Mech, ASCE* 134(12):1021–1028
- Blocken B, Janssen WD, van Hooff T (2012) CFD simulation for pedestrian wind comfort and wind safety in urban areas: general decision framework and case study for the Eindhoven University campus. *Environ Model Software* 30:15–34
- Bottema M (1993) Wind climate and urban geometry. PhD dissertation, Technische Universiteit Eindhoven, Faculteit Bouwkunde, Vakgroep Fago
- Castro IP, Graham JMR (1999) Numerical wind engineering: the way ahead? *Proc Inst Civ Eng Struct Build* 134:275–277
- Cochran LS (2004) Design features to change and/or ameliorate pedestrian wind conditions. In: Proceedings of the ASCE structures congress, Nashville, May 2004

- Ferreira AD, Viegas DX, Sousa ACM (1999) Numerical and experimental study of the wind flow around a group of low-rise buildings. In: Proceedings of the 10th international conference on wind engineering, Copenhagen, 21–24 June 1999
- Hoppe P (2002) Different aspects of assessing indoor and outdoor thermal comfort. *Energy Build* 34:661–665
- Hu C-H, Wang F (2002) Personal communication
- Isyumov N, Davenport AG (1975) The ground level wind environment in built-up areas. In: Proceedings of the 4th international conference on wind effects on buildings and structures, London
- Janssen WD, Blocken B, van Hooff T (2013) Pedestrian wind comfort around buildings: comparison of wind comfort criteria based on whole-flow field data for a complex case study. *Build Environ* 59:547–562
- Lawson TV, Penwarden AD (1975) Effect of wind on people in the vicinity of buildings. In: Proceedings of the 4th international conference on wind effects on buildings and structures, Heath-row, pp 605–622
- Melbourne WH (1978) Criteria for environmental wind conditions. *J Wind Eng Ind Aerodyn* 3: 241–249
- Miles SD, Westbury PS (2002) Assessing CFD as a tool for practical wind engineering applications. In: Proceedings of the 5th UK conference on wind engineering, University of Nottingham, Sept 2002
- Montazeri H, Blocken B, Janssen WD, van Hooff T (2013) CFD evaluation of new second-skin facade concept for wind comfort on building balconies: case-study for the Park Tower in Antwerp. *Build Environ* 68:179–192
- Murakami S, Iwasa Y, Morikawa Y (1986) Study on acceptable criteria for assessing wind environment on ground level based on residents' diaries. *J Wind Eng Ind Aerodyn* 24:1–18
- NEN (2006a) Wind comfort and wind danger in the built environment, NEN 8100 (in Dutch) Dutch Standard
- NEN (2006b). Application of mean hourly wind speed statistics for the Netherlands, NPR 6097:2006 (in Dutch) Dutch practice guideline
- Nicolopoulou M, Lykoudis S (2002) Thermal comfort in open spaces: the human factor. In: Proceedings of the 6th Panhellenic congress of meteorology, climatologic and atmospheric physics, Ioannina, 25–28 Sept 2002
- Nicolopoulou M, Baker N, Steemers K (2001) Thermal comfort in outdoor urban spaces: understanding the human parameter. *Sol Energy* 70(3):227–235
- Penwarden AD (1973) Acceptable wind speeds in towns. *Build Sci* 8:259–267
- Penwarden AD, Wise AFE (1975) Wind environment around buildings. *Building Research Establishment Digest*, Bracknell, Berkshire RG12 8FB
- Richards PJ, Hoxey RP (1992) Computational and wind tunnel modeling of mean wind loads on the Silsoe structures building. *J Wind Eng Ind Aerodyn* 41–44:1641–1652
- Stathopoulos T (2002) The numerical wind tunnel for industrial aerodynamics: real or virtual in the new millennium? *Wind Struct* 5(2–4):193–208
- Stathopoulos T (1997) Computational wind engineering: past achievements and future challenges. *J Wind Eng Ind Aerodyn* 67–68:509–532
- Stathopoulos T, Baskaran A (1996) Computer simulation of wind environmental conditions around buildings. *Eng Struct* 18(11):876–885
- Stathopoulos T, Wu H, Zacharias J (2004) Outdoor human comfort in an urban climate. *Build Environ* 39(3):297–305
- Timofeyef N (1998) Numerical study of wind mode of a territory development. In: Proceedings of the 2nd East European conference on wind engineering, Prague, 7–11 Sept 1998
- Tominaga Y, Mochida A, Shirasawa T, Yoshie R, Kataoka H, Harimoto K, Nozu T (2004) Cross comparisons of CFD results of wind environment at pedestrian level around a high-rise building and within a building complex. *J Asian Architect Build Eng* 3:63–70

- Venturi GB (1799) *Experimental enquiries concerning the principle of the lateral communication of motion in fluids: applied to the explanation of various hydraulic phenomena*. Translated from the French by W. Nicholson, 1st English Ed., J. Taylor, Architectural Library, High-Holborn, London
- Verkaik JW (2000) Evaluation of two gustiness models for exposure correction calculations. *J Appl Meteorol* 39(9):1613–1626
- Verkaik JW (2006) *On wind and roughness over land*. PhD thesis, Wageningen University, Wageningen, 123 pp
- Westbury PS, Miles SD, Stathopoulos T (2002) CFD application on the evaluation of pedestrian-level winds. Workshop on impact of wind and storm on city life and built environment, cost action C14, CSTB, Nantes, 3–4 June 2002
- Willemsen E, Wisse JA (2002) Accuracy of assessment of wind speed in the built environment. *J Wind Eng Ind Aerodyn* 90:1183–1190
- Willemsen E, Wisse JA (2007) Design for wind comfort in the Netherlands: procedures, criteria and open research issues. *J Wind Eng Ind Aerodyn* 95(9–11):1541–1550
- Wise AFE (1970) Wind effects due to groups of buildings. In: *Proceedings of the Royal Society symposium architectural aerodynamics, session 3, Effect of buildings on the local wind*, London, February 1970, pp 26–27
- Wisse JA, Willemsen E (2003) Standardization of wind comfort evaluation in the Netherlands. In: *Proceedings of the 11th international conference on wind engineering (11ICWE)*, Lubbock
- Wisse JA, Verkaik JW, Willemsen E (2007) Climatology aspects of a wind comfort code. In: *Proceedings of the 12th international conference on wind engineering (12ICWE)*, Cairns
- Zacharias J, Stathopoulos T, Wu H (2001) Microclimate and downtown open space activity. *Environ Behav* 33(2):296–315