Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples

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ABSTRACT: The construction of a building inevitably changes the microclimate in its vicinity. In particular near high-rise buildings, high wind velocities are often introduced at pedestrian level that can be experienced as uncomfortable or even dangerous. Therefore, the design of a building should not only focus on the building envelope and on providing good indoor environment, but should also include the effect of the design on the outdoor environment. The outdoor environment of a building, in particular related to wind, has received relatively little attention in the Building Physics community. The present paper addresses Building Physicists and focuses on the outdoor wind environment for pedestrians. First, a literature review on pedestrian wind studies is provided. The relation between wind effects, wind comfort, wind danger and wind climate is outlined. A brief review on wind tunnel and numerical modeling of building aerodynamics and pedestrian wind is given. The typical wind flow pattern around buildings and the related wind environment at pedestrian level are discussed. Second, these problems are illustrated by means of four practical examples, where the unfavorable pedestrian wind environment has been, is or should be a matter of serious concern for the building designers and the building owner.

KEY WORDS: outdoor climate, microclimate, wind climate, building, pedestrian comfort, wind comfort, wind tunnel, CFD.

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INTRODUCTION

BUILDING PHYSICS, AMONGST others, deal with the indoor and outdoor climate and the building envelope. The outdoor climate has received relatively little attention in the Building Physics community. Where it has been addressed, it has mainly been in order to provide boundary conditions for the study of the indoor climate and of the hygrothermal behavior and durability of the building envelope, but not for the outdoor climate itself (e.g. research concerning driving rain impact on buildings in order to provide boundary conditions for the study of moisture transfer in the building envelope) [1–11]. The construction of a building inevitably changes the outdoor climate at the building site (microclimate). Wind speed, wind direction, air pollution, driving rain, radiation and daylight are all examples of physical aspects that constitute the outdoor climate and that are changed by the presence of the building. The change of these quantities depends on the shape, size, and orientation of the building and on the interaction of the building with the surrounding buildings and other obstacles such as trees etc. These changes can be either favorable or unfavorable. Unfavorable changes include: (1) increased wind speeds around the building leading to uncomfortable or even dangerous conditions for pedestrians, (2) decreased wind speeds leading to insufficient removal and accumulation of traffic or industrial exhaust gases, (3) shadowing or reflection of sunlight by the building, (4) visual pollution (changed and/or blocked view), (5) acoustical changes, etc. Increased wind speed at pedestrian level is one of the problems that are considered most important. The present paper will be confined to this aspect of the outdoor climate.

The wind speed at pedestrian level results from the complex wind flow pattern around a building. Studies of pedestrian wind environment consequently involve the study of building aerodynamics in general. Starting from the 1960s, building aerodynamics has secured its place in scientific literature thanks to the construction and use of improved boundary layer wind tunnel facilities, which made it possible to accurately simulate the flow around buildings. Extensive studies have been conducted, mainly in the Wind Engineering community rather than in the Building Physics community: [12–15], to mention just a few. Yet, the study of building aerodynamics is of importance in almost all branches of Building Physics:

1. Indoor climate: indoor air quality and ventilation [16–26] and thermal comfort [27–30];

2. Building envelope: driving rain [31–45], rain penetration [16,46–48], weathering [49,50], air infiltration [47], convective heat losses [51–54], etc.
3. Outdoor climate: outdoor air quality [55–62] and pedestrian wind environment.

It must be noted that there are a few research groups that combine the study of the indoor climate and the building envelope with research on building aerodynamics and outdoor wind climate, such as the Building Physics Group FAGO at the Eindhoven University of Technology [63–70]. They also include these aspects in the teaching activities. A number of studies on outdoor wind environment have also been conducted at the Institute of Architecture and Urban Planning, Technical University of Lodz [71] and at the Laboratory of Building Physics, University of Leuven [72,73].

The importance of a comfortable and safe wind environment in the vicinity of buildings has been emphasized by a large number of authors. Uncomfortable wind conditions have proven detrimental to the success of new buildings [74]. Wise [75], for one, reports about shops that are left untenanted because of the windy environment that discouraged shoppers. Lawson and Penwarden [76] report dangerous wind conditions to be responsible for the death of two old ladies in 1972 after being blown over by sudden wind gusts near a high-rise building. Recognizing the importance of the outdoor wind climate, many urban authorities nowadays require studies of the pedestrian wind environment for large construction projects. The majority of studies in the past have been conducted with wind tunnel modeling. Recently, Computational Fluid Dynamics (CFD) has become available as an additional tool.

The aim of the present paper is threefold: it is an attempt (1) to stimulate the interest of the Building Physics community for the problem of wind nuisance around buildings, (2) to indicate the need for further research efforts, and (3) to indicate the need for inclusion of pedestrian wind studies in the design strategy of medium-rise and high-rise buildings. First, a literature review on pedestrian wind studies is provided. The relation between wind effects, wind comfort, wind danger, and wind climate is outlined. A brief review on wind tunnel and numerical modeling of building aerodynamics and pedestrian wind is given. The typical wind flow pattern around buildings and the related wind environment at pedestrian level are discussed. Second, these problems are illustrated by means of four practical examples, where the unfavorable pedestrian wind environment has been, is or should be a matter of serious concern for the building designers and the building owner.

WIND EFFECTS, WIND COMFORT, WIND DANGER, AND WIND CLIMATE

Wind Effects

A distinction is made between the mechanical and the thermal effects of wind. Mechanical effects of wind on people range from the feeling of a light breeze on the skin to being blown over by a strong gale. Lawson and Penwarden [76] have provided an extended "Land Beaufort Scale" showing wind effects on people (Table 1). The tabulated wind speed refers to the value that is measured at pedestrian height ($z = 1.75$ m) over open terrain with an aerodynamic roughness length z_0 of 0.03 m [77]. It is important to note that the measurement values are averaged over periods of 10 min or 1 h (steady wind). The wind effects mentioned however can be caused by both steady wind and wind gusts (turbulence).

Bottema [66] correctly distinguishes between mechanical wind effects caused by steady winds, by non-uniform winds and by wind gusts. Steady wind effects have been investigated by (in chronological order): Penwarden

Table 1. Extended Land Beaufort Scale showing wind effects on people [76].

Beaufort Number	Description	Wind Speed at 1.75 m height (m/s)	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 forwards 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

[78], Hunt et al. [79], Penwarden et al. [80], Murakami et al. [81], Murakami [82], and Bottema [66]. From an extensive study, Murakami et al. [81] have found that (1) a steady wind of 5 m/s only causes a minor disturbance of hair and clothes and wind is felt on the face, (2) a steady wind of 10 m/s causes hair to be disturbed and fluttering clothes, while (3) a steady wind of 25–33 m/s will blow people away. Comparing these values with the values in Table 1 provides an indication of the importance of wind gusts in wind effects. The effects of non-uniform winds on people have been studied by Murakami et al. [81]. In a wind tunnel, people were asked to walk through a jet of strong side winds and footstep irregularities were monitored. It was found that these irregularities were roughly comparable with wind effects in uniform flow with a speed of 1.5 times the wind speed in the jet. The effects of gust winds on people have been studied by (in chronological order): Hunt and Poulton [83], Hunt et al. [79], Jackson [84], Murakami et al. [81,85], Murakami [82] and Bottema [66]. According to calculations by Bottema [66], a sudden increase of wind speed to 15 m/s or more can be sufficient to bring people out of balance. Summarizing the results of other researchers, Bottema [66] states that: (1) a gust of 4 m/s during 5 s causes hair to be disturbed and clothes to flap, (2) a gust of 7 m/s during 5 s can cause hair to be disarranged, (3) a gust of 15 m/s during 2 s can bring people out of balance and is dangerous for the elderly and the infirm, (4) a gust of 20 m/s can be dangerous, even for young people and (5) a gust of 23 m/s will blow people over. Comparing these values with those given above for steady winds (Murakami et al. [81]) again indicates the importance of wind gusts in wind effects: for the same wind effect, gust wind speeds are significantly less.

Assessing the thermal effects of wind on people is complex because of the large number of parameters involved: mean wind speed, gust speed, gust duration, air temperature, air humidity, radiation, metabolism, exposure time, clothing, moisture content of the clothes, air permeability of the clothes, etc. Thermal comfort has been addressed by (in chronological order): Humphreys [86], Steadman [87], Fanger [88], Penwarden [78], Hunt [89], Lawson and Penwarden [76], Hunt et al. [79], Steadman [90], and Fanger et al. [91], to mention just a few. Lawson and Penwarden [76] concluded that, within certain limitations, the criteria of acceptability for thermal comfort will automatically be satisfied, provided that the criteria for mechanical comfort are met. On the other hand, a considerable amount of research on outdoor thermal comfort has been performed recently [92–101]. The present paper provides no answer to the question if, when, and where thermal effects and thermal comfort should be included. It will be confined to dealing with mechanical effects and mechanical wind comfort and wind danger only.

Wind Comfort

Wind effects do not necessarily imply wind discomfort. Bottema [102] defines pedestrian discomfort as:

> "Pedestrian discomfort occurs when wind effects become so strong and occur so frequently (say on time scales up to 1 h), that people experiencing those wind effects will start to feel annoyed, and eventually will act in order to avoid these effects."

According to this definition a suitable wind comfort criterion may consist of a discomfort threshold and an exceedence probability of the threshold. A discomfort threshold is the minimum wind speed and turbulence level for uncomfortable conditions. Discomfort thresholds are generally of the form:

$$U_e = U + k \cdot \sigma_u > U_{\mathrm{THR}} \tag{1}$$

where U_e is the equivalent wind speed, U is the mean wind speed, k is the peak factor, σ_u is the standard deviation of the wind speed (turbulence) and U_{THR} is the threshold value (all at pedestrian height). Different authors have proposed different values for k and U_{THR}. However, experimental comfort investigations, as opposed to experimental investigations on wind effects, are very scarce. Most discomfort thresholds have been based on the combination of wind effect studies and intuition rather than on comfort investigations [76,83,85,103–109]. Important psychological comfort investigations supporting discomfort thresholds are the wind tunnel experiments by Hunt et al. in 1976 [79] and the outdoor comfort investigation by Jackson in 1978 [84]. The results of Jackson's street survey were adopted and corrected by Bottema [66], yielding a peak factor ($k = 1$). Bottema [66] proposes:

$$U_e = U + \sigma_u > 6\,\mathrm{m/s} \tag{2}$$

It is noted that this threshold is only valid for walking. For other human activities, other thresholds might be more suitable.

In general, comfortable conditions cannot always be met and uncomfortable conditions must be accepted for a certain percentage of time. Discomfort probability and danger probability are defined as the percentage of hours (during a year) in which the thresholds are exceeded. The maximum allowed percentage will depend on the type of human activity that is planned. As was the case with the thresholds, also the maximum acceptable discomfort probability has generally been based on intuition. An important experimental investigation on discomfort probabilities has been reported by Lawson and Penwarden in 1975 [76]. They analyzed the complaints of owners of shops that were mainly situated near high-rise buildings. The criterion found by these researchers (threshold + maximum discomfort probability) is therefore often referred to as "the shop owners criterion". The maximum allowed discomfort probability found by Lawson and Penwarden [76] has been adopted and corrected by Bottema [66]: $P_{max} = 15\%$ (for strolling/walking).

Many comfort criteria have been suggested and used in the past [76,79, 85,103,105–110]. A number of researchers have provided criteria comparisons. Whereas Melbourne [107] and Visser [108] from a comparative study concluded that the existing criteria showed a satisfactory agreement, other researchers found considerable differences [111–114]. Bottema has recently made an impressive comparison of about 30 criteria, revealing differences that were not known before [66,102]. Large and sometimes very large differences were found between criteria, most likely due to the fact that most criteria (both thresholds and maximum discomfort probabilities) have been based on intuition. Experimental evidence supporting the choice of a suitable criterion is provided by the shop owners criterion of Lawson and Penwarden and by the long-term survey (two years of residents' diaries) by Murakami et al. [85]. Based on this information and on his comparison study, Bottema [102] selected the criterion given by Equations (3) and (4). The discomfort threshold results from Jackson's field data [84], the maximum allowed discomfort probability is taken from Lawson and Penwarden [76]. As mentioned earlier, both were corrected by Bottema [102]:

$$U_e = U + \sigma_u > 6\,\text{m/s} \tag{3}$$

$$P_{max} = 15\% \tag{4}$$

Wind Danger

As opposed to wind comfort, wind danger can be directly related to wind effects. Danger thresholds have been proposed by (in chronological order): Melbourne and Joubert [115], Isyumov and Davenport [103], Hunt et al. [79], Melbourne [107], Murakami et al. [85] and Williams and Soligo [109]. From the outdoor observations of Melbourne and Joubert [115] during a storm, Hunt et al. [79] proposed the threshold Equation (5) for 'control of walking' and Equation (6) for 'danger'.

$$U + 3\sigma_u > 15\,\text{m/s} \tag{5}$$

$$U + 3\sigma_u > 20\,\text{m/s} \tag{6}$$

The first threshold 'control of walking' can be considered as a danger threshold for the elderly whereas the second is valid for average people [79]. Maximum acceptable danger probabilities are $P_{max} = 1$ h per year [103,107] or 0.1% [109].

Wind Climate

The assessment of wind climate at a particular location requires the combination of (1) statistical meteorological data, (2) aerodynamic information and (3) a comfort criterion. Meteorological information comprises long-term wind statistics from a meteorological station in open terrain. Aerodynamic information is needed to transform the meteorological information from the weather station to the building site where the wind climate is to be assessed. Once this link is established providing us with the wind statistics at the location of interest, the comfort criterion is used to judge local wind climate.

METEOROLOGICAL DATA

The meteorological data should cover a period of several decades (typically 30 years) and should be exposure corrected. Generally, measurements at a meteorological site are influenced by the surroundings (forests, villages, etc...) of the site. Exposure corrections are applied to remove these influences. A number of meteorological institutes provide corrected data in the form of hourly values of potential wind speed (U_{pot}) and wind direction. The potential wind speed U_{pot} is defined as the wind speed measured at 10 m height at an ideal meteorological station with an aerodynamic roughness length $z_0 = 0.03$ m. The data is usually given in 12 wind direction sectors of 30°. The frequency distribution of the hourly mean wind speed can often with good accuracy be described by a cumulative Weibull distribution [116]:

$$P_\theta\left(U_{pot} > U_{THR,pot}\right) = 100 \cdot A(\theta) \exp\left[-\left(\frac{U_{THR,pot}}{c(\theta)}\right)^{k(\theta)}\right] \tag{7}$$

where $U_{THR,pot}$ is a certain threshold value for the potential wind speed, $P_\theta(U_{pot} > U_{THR,pot})$ is the probability of exceedence of $U_{THR,pot}$ by U_{pot} during wind direction θ, and $A(\theta)$, $c(\theta)$ and $k(\theta)$ are the Weibull parameters, respectively denoting: probability for wind direction θ, velocity scale for wind direction θ (m/s), shape parameter for wind direction θ.

The Weibull parameters are determined by fitting Equation (7) to the meteorological data.

AERODYNAMIC INFORMATION

The wind statistics measured at the meteorological site (mean wind speed U_{pot}, wind direction, and the longitudinal gust speed or standard deviation σ_u) must be transformed to the building site. For the mean wind speed, the transformation is performed by means of the wind amplification factor γ (Equation 8):

$$\gamma = \frac{U}{U_{pot}} \tag{8}$$

where U is the local wind speed at the building site. To determine the wind amplification factor, the ratio U/U_{pot} can be split into two factors: a design-related contribution U/U_0 and a terrain-related contribution U_0/U_{pot} [66].

$$\gamma = \frac{U}{U_{pot}} = \frac{U}{U_0} \cdot \frac{U_0}{U_{pot}} \tag{9}$$

where U_0 is a reference wind speed that is taken at a certain distance upstream of the building site. The design-related contribution comprises the influence of the building geometry, building orientation, the interaction between buildings, etc., all at the building site. It depends on the design of the buildings and their surroundings. It can be determined by wind tunnel or numerical (CFD) modeling. The terrain-related contribution takes into account the differences in terrain roughness between the meteorological site and the terrain surrounding the building site. In the interest of brevity, the complete procedure to determine the wind amplification factor is not included in this paper. The reader is referred to [73]. Following this procedure, separate values for the conversion factor γ_θ are obtained for each wind direction θ.

According to Bottema et al. [65] and Bottema [66], pedestrian level σ_u is approximately constant and σ_u at the building site can be assumed equal to σ_u at the meteorological site. If no information about the standard deviation σ_u is available from the meteorological station (e.g. only the frequency table of mean wind speed and wind direction is provided), it can be taken equal to 2.4 u^* [117], where u^* is the friction velocity at the meteorological station. For $U \approx 6$ m/s, it can be calculated that $\sigma_u \approx 1$ m/s [73]. Where the wind direction is concerned, it is generally assumed that the directional distribution of wind statistics over the 30° sectors is maintained in the transformation.

COMFORT CRITERION AND WIND CLIMATE ASSESSMENT

We adopt the criterion selected by Bottema [66,102] from his comparison study (Equations (3) and (4)). The threshold value for the effective wind speed is 6 m/s, the maximum allowed discomfort probability $P_{MAX} = 15\%$. With $\sigma_u \approx 1$ m/s, the exceedence of the criterion wind speed threshold value $U_{THR} = 6$ m/s by the local effective wind speed U_e (see Equation (10)) is equal to the exceedence of the threshold value $\tilde{U}_{THR} = 5$ m/s by the local mean wind speed U (see Equation (11)).

$$U_e = U + \sigma_u > 6\,\mathrm{m/s} = U_{\mathrm{THR}} \tag{10}$$

$$U_e - \sigma_u = U > 5\,\mathrm{m/s} = \tilde{U}_{\mathrm{THR}} \tag{11}$$

Equation (7) expresses the exceedence of a threshold value $U_{THR,pot}$ by the mean potential wind speed U_{pot}. Our interest however is in the exceedence of the threshold value $\tilde{U}_{THR}$ by the local mean wind speed U. Equation (7) applying to the potential wind speed must therefore be converted to an equation applying to the local wind speed. This can be done using the conversion factors γ_θ. As requirement (12) equals requirement (13), the exceedence probability of $\tilde{U}_{THR}$ by the mean local wind speed U is given by Equation (14).

$$U > \tilde{U}_{\mathrm{THR}} \tag{12}$$

$$U_{\mathrm{pot}} > \frac{\tilde{U}_{\mathrm{THR}}}{\gamma_\theta} = U_{\mathrm{THR,pot},\theta} \tag{13}$$

$$P_\theta = P_\theta\big(U > \tilde{U}_{\mathrm{THR}}\big) = 100 \cdot A(\theta) \exp\left[-\left(\frac{\tilde{U}_{\mathrm{THR}}}{\gamma_\theta \cdot c(\theta)}\right)^{k(\theta)}\right] \tag{14}$$

Calculating and summing P_θ for all wind directions yields the total discomfort probability P that should not exceed the maximum allowed value P_{MAX}.

Recent research has provided information about the way in which P_{MAX} must be reduced to account for errors in the calculation of the wind amplification factor γ [68]. Information about errors in γ has been provided by several authors [66,68–70]. The error in γ will cause a standard error in the calculated probability P that the local wind speed exceeds a threshold value. From a wind tunnel test for a given building configuration and from the Amsterdam airport meteorological data, Willemsen and Wisse [68] have provided an estimate for this error in P: $\delta P = 3\%$ for a threshold wind speed $\tilde{U}_{THR} = 5\,\text{m/s}$ and for a value $P_{MAX} = 15\%$. From this estimate and assuming a normal distribution for the error in P and in order to get a 95% confidence level, they propose a corrected value for the maximum allowed discomfort probability (Equation (15)). In wind climate assessment, this corrected, more stringent value should be used.

$$P_{\max,\text{cor}} = P_{\max} - (1.6 \cdot 3)\% = 10\% \tag{15}$$

The above procedure has focused on wind comfort. A similar procedure can be followed for wind danger. To take into account the errors in γ in wind danger studies, the results of Willemsen and Wisse [68] indicate that for $\tilde{U}_{THR} = 15\,\text{m/s}$ and $P_{\max}$ from 0 up to 1% and more, the corrected value for the maximum allowed danger probability should be set to 0%.

The following section will be devoted to the study of building aerodynamics and pedestrian wind in wind tunnels and by numerical modeling. It is noted that this is an essential part in wind climate assessment (determination of the design-related contribution U/U_0 of the wind amplification factor γ). Yet, it is treated separately, partly due to its importance and partly because it has generally been studied as a stand-alone subject in literature.

BUILDING AERODYNAMICS AND PEDESTRIAN WIND

Wind Tunnel Modeling

Before being applied in building aerodynamics, wind tunnel modeling had been practiced in the aeronautical field. The wind tunnels used were specifically designed for aircraft studies, with a uniform wind speed across the tunnel section and with low turbulence. The first attempts to model building aerodynamics were made using these aircraft tunnels. As an example, Chien et al. [118] tested elementary building forms in a wind tunnel to determine the pressure distribution. They produced a catalogue of their results, which has been widely used by structural engineers. All tests were performed with the velocity constant at all heights above ground. However, at that time it had already been recognized that such wind tunnel results are not representative of full-scale flow around buildings [119]. It appeared that modeling the variation of the mean velocity with height, as present in the Atmospheric Boundary Layer (ABL), is essential for reliable results to be obtained. Later publications emphasized this statement [120–126]. As a result, new wind tunnels were constructed that specifically take into account the increase of wind speed with height (boundary layer wind tunnels). The increase with height can approximately be represented by a logarithmic function (the log law: Equation (16)) or by a power function (the power law: Equation (17)) [127,128].

$$U(z) = \frac{u*}{\kappa} \cdot \ln\left(\frac{z}{z_0}\right) \tag{16}$$

$$\frac{U(z)}{U_{\text{ref}}} = \left(\frac{z}{z_{\text{ref}}}\right)^{\alpha} \tag{17}$$

where $U(z)$ is the horizontal wind speed at height z, $u*$ is the friction velocity, κ is the von Karman constant (≈ 0.4; [117]), z_0 is the aerodynamic roughness length [77], U_{ref} is the reference wind speed at reference height z_{ref} and α is the power law exponent. Figure 1 illustrates the difference between both laws and the uniform velocity distribution, all with a reference wind speed $U_{\text{ref}} = 10$ m/s fixed at a height of 10 m and with parameters $z_0 = 0.6$ m and $\alpha = 0.28$. The values of z_0 and α (urban terrain) were matched with each other, therefore both laws yield similar profiles.

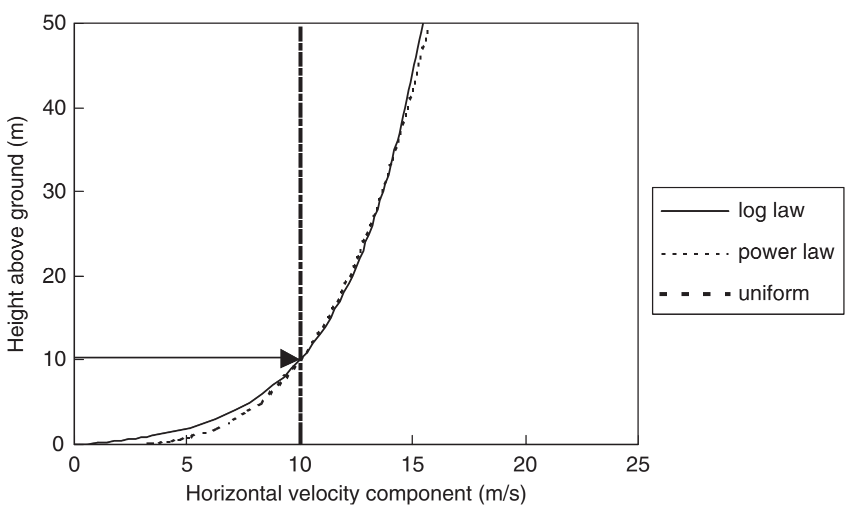

Figure 1. *The variation of horizontal wind speed with height above ground: the logarithmic law (log law), the power law and the uniform velocity distribution, all with a reference wind speed $U_{ref} = 10$ m/s at a height of 10 m. Parameters for the log law and the power law are $z_0 = 0.6$ m and $\alpha = 0.28$ respectively (urban terrain). The values of z_0 and α were matched with each other, therefore both laws yield similar profiles.*

The earliest studies in building aerodynamics in general and in boundary layer wind tunnels in particular were mainly concerned with wind loading (pressure distributions) and the dynamic effects of wind on buildings and structures. It was only from the sixties that airflow around buildings and pedestrian wind environment was given a significant amount of attention, as building designers were increasingly being confronted with the poor wind environment around their creations. Wise [75] reports that apart from inquiries concerning wind loading, the wind environment in pedestrian precincts around groups of tall buildings has brought in the greatest number of inquiries to the Building Research Station (BRS) in the sixties; some 200 inquiries were received between 1964 and 1970. A number of these have been studied in detail in the BRS wind tunnel. In order to provide general information, also studies of airflow around idealized model buildings have been conducted at the BRS [16,75,129]. As an example, Figure 2 [129] shows a photograph of a smoke visualization test in the wind tunnel in which the flow around a slab block screened by a low building was visualized. Two phenomena can be observed: (1) The division of the flow when meeting the windward face of the slab: from the stagnation point at about 2/3 of the height, the flow divides with some of it passing upwards, some passing sidewards and the remainder descending to the base of the slab; (2) The large standing vortex in the space between the low building and the slab that is generated by the down-flow of air from the stagnation point. For the same configuration, Figure 3 [16] shows smoke injected into the airstream from small orifices in the windward face of the slab. The division of the flow from the stagnation point is visualized.

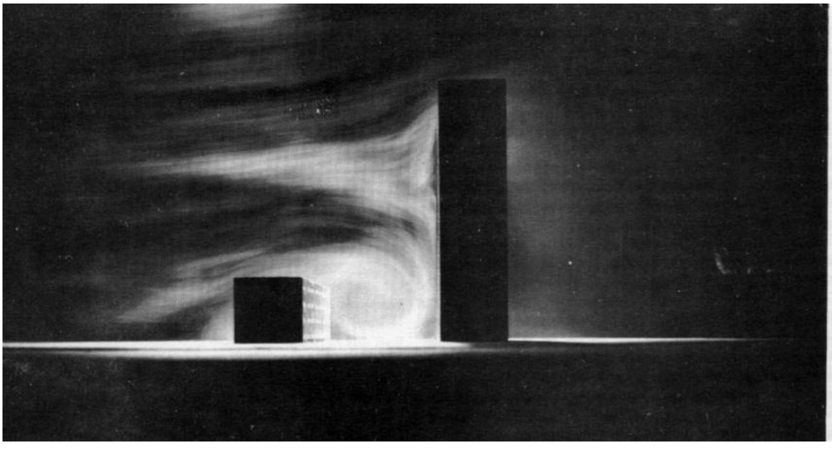

Figure 2. *Smoke visualization test in a wind tunnel illustrating the flow around a slab block screened by a low building [129] (reproduced with permission, © BRE 2003).*

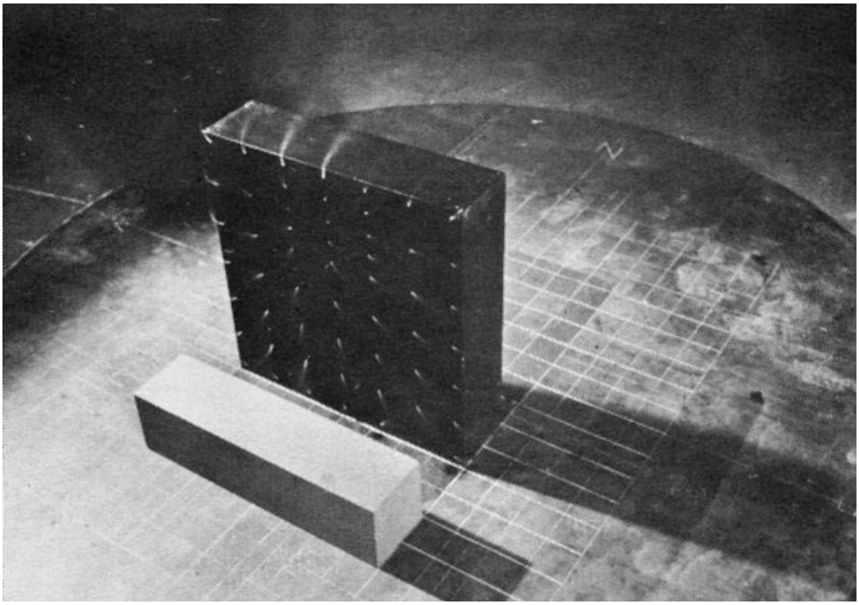

Figure 3. *Smoke visualization test in a wind tunnel. Smoke is injected into the airstream from small orifices in the windward face of the slab illustrating the division of the flow [16] (reproduced with permission, © BRE 2003).*

At the stagnation point, the injected smoke is only visible as a white dot. At the other facade positions, a short smoke streak indicates the local wind direction. In addition to the smoke tests, velocity measurements were conducted and flow ratios were obtained by dividing the wind speed values by the wind speed that would occur at the same height if the buildings were absent. Typical results are given in Figure 4 [16]. The largest ratio is found near ground level in the standing vortex (value 1.3). Not indicated in this figure, but for a similar configuration, Wise et al. [129] measured a ratio of 1.6 in the corner streams. The corner streams are defined as the typical high wind speed regions downstream of upwind building corners that are fed by the standing vortex. These early investigations, and many others afterwards, have pointed to the general conclusion that tall buildings tend to bring down higher speed air to the ground and that especially the corner streams and the standing vortex can negatively affect the pedestrian wind environment.

Further wind tunnel studies of pedestrian wind around buildings have been reported by a large number of authors. Wind tunnel studies for idealized model buildings have been performed by for example, (in chronological order) Gandemer [104], Wiren [130], Lawson and Penwarden [76], Penwarden and Wise [131], Beranek and Van Koten [132], Beranek [133],

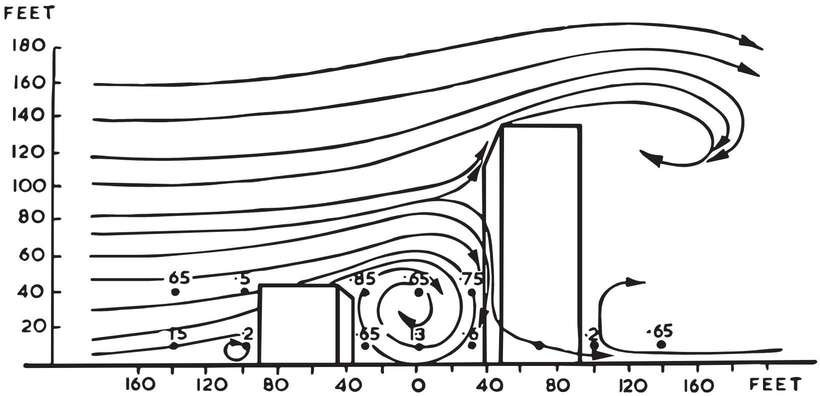

Figure 4. *Wind speed ratios measured in a wind tunnel test. The ratios were obtained by dividing the measured wind speed values by the wind speed that would occur at the same height if the buildings were absent [16] (reproduced with permission, © BRE 2003).*

Beranek [110,134], Kenworthy [135] and Stathopoulos and Storms [136]. These studies have all provided increased insights into the pedestrian wind environment around buildings. They also provide a basis from which general guidelines, rules of thumb and empirical formulae can be established [137]. This information can be used for the development of knowledge-based expert systems (KBES) [138–140]. KBES allow a preliminary and simplified evaluation of the pedestrian wind environment around buildings. They are constructed by combining general guidelines, rules of thumb, empirical formulae, additional wind tunnel measurements, meteorological data, wind comfort criteria and an easy-to-use user-interface. This way academic research results can be applied in engineering practice. These simplified predictions can in turn be validated by wind tunnel measurements as has been successfully done by Stathopoulos et al. [138] and Visser et al. [140]. Knowledge-based expert systems can provide a simplified indication of the high wind speed areas around buildings. However, in the case of complex building configurations or when the effects of building details need to be evaluated, full wind tunnel studies (case studies) have to be carried out: for example, (in chronological order) Isyumov and Davenport [103,141], Sparks and Elzebda [111], Lohmeyer et al. [142], Gerhardt and Kramer [143,144], Williams and Wardlaw [145], Richards et al. [146], Ferreira et al. [147], Westbury et al. [148]. If the results indicate that wind conditions are unfavorable, remedial measures should be contemplated. Wind tunnel studies examining the effect of various remedial measures have been reported by (in chronological order): Isyumov and Davenport [103], Wiren [130], Penwarden and Wise [131], Beranek [133], Beranek [134], Merati et al. [149], Uetmatsu et al. [150], Jamieson et al. [151] and Lam [152].

Finally, some authors have compared their wind tunnel results with full-scale measurements (in chronological order: Melbourne and Joubert [115], Isyumov and Davenport [141], Bottema et al. [65], Visser and Cleijne [153]) and some authors have conducted wind tunnel experiments to be used for the validation of CFD calculations of pedestrian wind (in chronological order: Bottema et al. [64,65], Gadilhe et al. [154], Stathopoulos and Baskaran [155], Richards et al. [146], Ferreira et al. [147], Westbury et al. [148]).

Wind Tunnel Measurement Methods for Pedestrian Wind

Methods for studying pedestrian level wind conditions in wind tunnels can be divided into two groups: point methods and area methods. Point methods provide quantitative data at discrete locations in the flow field. The sensors used can be hot-wire anemometers, hot-film anemometers, thermistors, pressure sensors or optical dynamometers [132,156–161]. Area methods provide spatially continuous qualitative information. These methods can include scour techniques [110,132–134,142,158,160,162,163], the use of oil streaks [110,134,162,165] or infrared thermography [139,166, 167]. The advantage of area methods is that a complete visualization of the pedestrian level wind flow over the entire area of concern is obtained. Establishing this kind of visualization with point methods would require measurements on a high-density grid with a large amount of data processing. As the scour technique and oil streak technique will be used further in this paper, they will now be described in more detail.

The scour technique consists of two steps. In the first step (calibration step), the wind tunnel turntable floor (without building model) is sprinkled with a uniform fine layer of dried sand. Let U_{WT} denote the wind tunnel speed that is set by the operator of the tunnel (e.g. the speed of the fan). U_{WT} is increased in steps until at a certain wind speed value ($U_{WT,E}$) the sand is blown away. In the second step, the building model is placed on the turntable and the floor is sprinkled again with a uniform fine layer of sand. Again, the wind tunnel speed is increased in steps ($U_{WT,1}$, $U_{WT,2}, \ldots$) and the sand erosion that occurs at each step is allowed to reach a steady state. The areas in the flow field where sand is eroded are then registered by photography. From this information, a rough idea of the local amplification factor can be obtained as follows (the local amplification factor is defined here as the local wind speed divided by the wind speed that would occur at the same location if the buildings were absent). Let us focus on Figure 5. For each wind tunnel speed U_{WT}, we have a corresponding U_G and U_{GB} speed. U_G denotes the ground-level wind speed that is not influenced by the building. U_{GB} denotes the ground-level wind speed that is influenced by the building and for which sand erosion occurs (U_{GB} is only

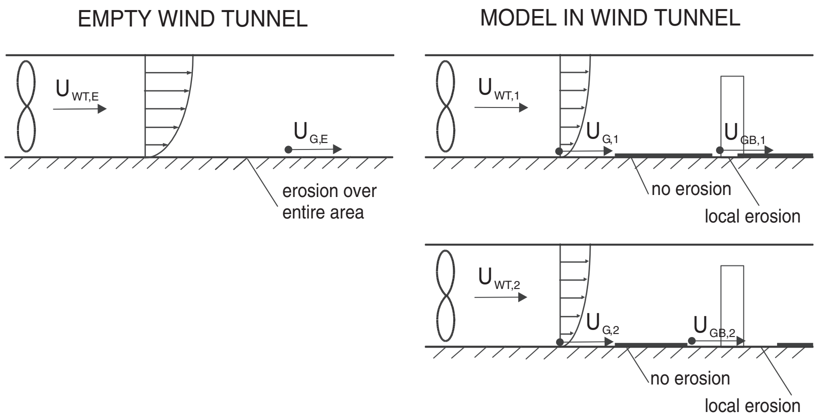

Figure 5. *Schematic representation of the procedure for the sand erosion technique.*

present at a particular area around the building, i.e. the area where the sand is eroded). In order to determine the local amplification factor around the building, we combine the following statements:

1. The local amplification factor in each step is equal to the ratio U_{GB}/U_G
2. U_G is proportional to U_{WT}, Equation (18)
3. U_{GB} is the same for all wind speed steps (sand erosion occurs always at the same ground-level wind speed), Equation (19)
4. For the empty wind tunnel, U_{GB} is equal to U_G (no building present), Equation (20)

$$\frac{U_{G,1}}{U_{WT,1}} = \frac{U_{G,2}}{U_{WT,2}} = \ldots = \frac{U_{G,E}}{U_{WT,E}} \tag{18}$$

$$U_{GB,1} = U_{GB,2} = \ldots = U_{GB,E} \tag{19}$$

$$U_{GB,E} = U_{G,E} \tag{20}$$

In these equations the indices E, 1, 2,... denote the different wind speed steps. Combining Equations (18)–(20) yields the expression for the local wind amplification factors:

$$\frac{U_{GB,1}}{U_{G,1}} = \frac{U_{WT,E}}{U_{WT,1}}; \frac{U_{GB,2}}{U_{G,2}} = \frac{U_{WT,E}}{U_{WT,2}}; \cdots \tag{21}$$

Remark: This result can also be found intuitively: when the building model is placed in the wind tunnel and the wind tunnel speed is gradually increased from zero, the first sand erosion will occur at an operating speed $U_{WT,1}$ that is smaller than $U_{WT,E}$ because the presence of the building introduces increased wind speeds at ground level. The ground level wind speed at which erosion occurs can be considered to have increased by $U_{WT,E}/U_{WT,1}$, i.e. the local amplification factor. Note that only the wind tunnel operating speed and not the ground speed must be measured to determine the local amplification factor. This way, it appears that quantitative information can be obtained. However, from comparisons of the scour technique with quantitative data from hot-wire measurement results, Livesey et al. [164] reported that as wind speeds inferred from scour data have considerable variability, these data are most suited for describing less quantitative measures of the wind flow where relative, rather than absolute information is needed.

The oil streak technique consists of coating the wind tunnel floor around the model with a mixture of kaolin and paraffin oil. As the air flows over the mixture and drives it over the turntable, the paraffin oil evaporates. The result is a pattern of streaks clearly showing the mean direction of the wind flow near the floor. The type of the streaks (shape and density) also provides some information on the turbulence in the flow. The oil streak technique can be used in addition to the scour technique that provides no directional information.

Numerical Modeling

Numerical modeling with CFD (Computational Fluid Dynamics) can provide an alternative for wind tunnel studies. It has the advantage of being less time consuming and less expensive than wind tunnel modeling and it directly yields the detailed wind flow at every point around the configuration studied. The major disadvantage is the need for model validation in order to use this tool with confidence.

CFD simulations of building aerodynamics in general (not pedestrian wind in particular) have been performed by a large number of authors. Publications that specifically focus on the wind flow pattern around buildings, rather than only the wind pressure on building faces, are – among others – [168–197].

CFD modeling of pedestrian level wind in particular has been performed by only a small number of authors. One of the first CFD calculations with the attention focused on the pedestrian wind environment was that conducted by Bottema et al. in 1992 [65]. Flow around a single, wide block and in a group of blocks was studied and compared with wind tunnel measurements. Later, in 1993, Gadilhe et al. [154] simulated the wind flow through a semi-circular square. Takakura et al. [198] numerically predicted the harmful strong wind areas around high-rise buildings in an urban area. Both authors compared their numerical results with wind tunnel measurements. Bottema (1993) [66] provided an admirable amount of CFD calculations of pedestrian wind around single buildings and building groups with varying configurations. Baskaran and Kashef [199] studied the flow around a single building, between two parallel buildings and around a multiple building configuration. For the latter two situations, they conducted a model validation using the available wind tunnel results of Stathopoulos and Storms [136], Wiren [130,200] and Ishizaki and Sung [201]. An agreement ranging from satisfactory to very good was found for the parallel buildings. For the multiple-building configuration, the agreement was somewhat less. Stathopoulos and Baskaran [155] simulated pedestrian wind around a particular building group and compared the numerical results with the corresponding wind tunnel measurements, finding good agreement for most measurement positions. He and Song [202] used LES (Large Eddy Simulation) to obtain information on both the mean wind speed and the turbulence characteristics around a building group. Richards et al. [146] built a large numerical model to simulate pedestrian level wind speeds in downtown Auckland. The numerical results were compared with corresponding results of the scour erosion technique. Although the patterns appeared similar, noticeable discrepancies were found. The authors attributed the differences to the fact that wind tunnel tests are sensitive to gust wind speeds while the CFD method yields mean wind speeds. Further calculations were performed by (in chronological order): Ferreira et al. [147], Wisse et al. [70], Hirsch et al. [203], Westbury et al. [148] and Blocken et al. [72,73]. The latter authors have compared numerical and wind tunnel results for wind flow in passages through buildings, finding a satisfactory agreement for this particular flow zone.

Although some efforts towards CFD validation for pedestrian wind have been conducted, a systematic validation for a large number of buildings and building groups in different configurations has not yet been achieved. This can be attributed to the lack of available experimental data. There are only very few researchers that have published their experimental data in a form suitable for CFD validation. Summers et al. [170], Minson et al. [204] and Akins and Reinhold [205] have provided tabulated values of their point measurements. Their studies however did not specifically focus on pedestrian wind and were limited to a single rectangular building. Wiren [130] graphically reported his results of pedestrian wind flow studies in passages between and through buildings of varying geometry. Stathopoulos and Storms [136] conducted wind tunnel studies of the flow in passages between buildings of the same and of different heights. The results were represented graphically. An impressive and systematic database of wind tunnel sand erosion and oil streak tests was provided by Beranek and Van Koten [132] and Beranek [133]. However, as mentioned by Livesey et al. [164], this type of data is useful for qualitative rather than quantitative validation purposes. Reviewing the literature has led to the conclusion that there is an urgent need for systematic experimental studies on pedestrian wind flow around different building configurations and the publication of these data to be used for CFD validation. The need for validation data had already been expressed by Bradshaw in 1972 [206], by Summers et al. in 1986 [170] and by Baskaran and Kashef in 1996 [199] and is still present today. This applies for building aerodynamics in general but even more for pedestrian wind.

Wind Flow around a Single High-rise Rectangular Building

In the following, the wind flow pattern around a single building as known from full-scale, wind tunnel and CFD studies will be discussed. The wind flow pattern in general and at pedestrian level in particular will be addressed. The discussion is supported by drawings and wind tunnel measurement results of Beranek and Van Koten [132]. The figures are reproduced with permission (© Kluwer).

Figure 6(a) provides a schematic illustration of the wind flow pattern around a single wide high-rise building slab. As the wind flow approaches the building, it gradually diverges. Part of the flow is deviated over the building (1) and part of it flows around the building (2). At the windward facade, a stagnation point with maximum pressure is situated at approximately 70% of the building height. From this point, the flow is deviated to the lower pressure zones of the facade: upwards (3), sidewards (4) and downwards (5). The considerable amount of air flowing downwards produces a vortex at ground level (6) called standing vortex, frontal vortex or horseshoe vortex. The main flow direction of the standing vortex near ground level is opposite to the direction of the approach flow. Where both flows meet, a stagnation point with low wind speed values is created at the ground in front of the building (7). The standing vortex stretches out sideways and sweeps around the building corners where flow separation occurs and corner streams with high wind speed values are created (8). The corner streams subsequently merge into the general flow around the corners (9). At the leeward side of the building, an underpressure zone is created. As a result, backflow or recirculation flow occurs (10,13). A stagnation zone is marked downstream of the building at ground level where the flow directions are opposite and low wind speeds exist (11; end of the recirculation zone). Beyond the stagnation zone, the flow resumes its normal direction but wind speeds stay low for a considerable distance behind the building (i.e. the far wake) (12). The backflow is also responsible for the

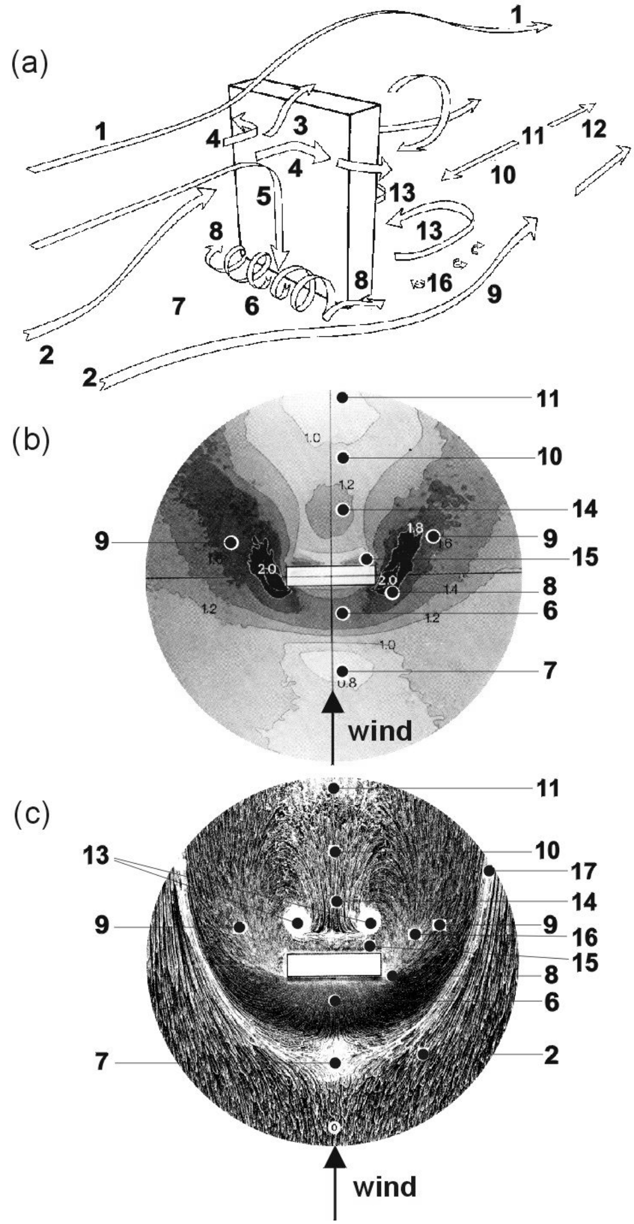

Figure 6. *Wind flow around a single wide high-rise rectangular building: (a) schematic representation; (b) sand erosion contour plot; and (c) kaoline streak line plot obtained from wind tunnel tests on a building with full-scale dimensions* $L \times B \times H = 80 \times 20 \times 70\,m^3$ *[132] (reproduced with permission, © Kluwer).*

creation of slow rotating vortices behind the building (13). Between these vortices and the corner streams (9), a zone with a high velocity gradient exists (the shear layer) that comprises small, fast rotating vortices (16). The shear layers originate at the building corners where flow separation occurs.

In fact, two pressure systems are present that determine the flow pattern. The first pressure system acts on the front facade of the building, with maximum pressure at the stagnation point and lower pressures at the rest of the facade. This pressure system is created by the increase of the approach flow wind speed with height (Figure 1) and is responsible for the occurrence of the standing vortex that in turn feeds the corner streams. The second pressure system consists of the overpressure zone at the windward side of the building and the underpressure zone at the leeward side. It is responsible for the recirculation (backflow) downstream of the building and also contributes to the corner streams. Both pressure systems are responsible for the complex wind flow pattern that is present around a building.

Figure 6(b) and (c) illustrate the pedestrian level wind. Figure 6(b) results from the sand erosion technique and presents contours of local amplification factor for a high-rise slab placed in urban terrain and with full-scale dimensions $L \times B \times H = 80 \times 20 \times 70\,\mathrm{m}^3$. Factors larger than unity indicate that the presence of the building increases the local wind speed, factors smaller than unity indicate that the building provides shelter at these locations. Figure 6(c) is the result of the oil streak technique for the same building. It is observed that the horseshoe vortex in front of the building causes high wind speeds with the main flow direction away from the building (6). The name horseshoe vortex refers to the shape in which the vortex wraps around the building. The stagnation zones at ground level in front of the building (7) and behind the building (11) are indicated as white areas in Figure 6(c), as no clear streaks were made. Figure 6(b) and (c) show that the corner streams (8) are merging into a broad band of increased wind speeds (9) that extends for a considerable distance downstream of the building. Between the building and the stagnation zone (11), increased wind speed is generated by the recirculating backflow (14). Directly behind the building, significant wind streams rising at the leeward side practically parallel to the building facade are observed (15). The slowly rotating vortices (13) behind the building are clear in Figure 6(c) as white spots. Number (17) marks what Beranek and Van Koten [132] call "the influence area" of the building, i.e. the area where wind speed is significantly influenced by the presence of the building. Finally, it is noted that the streamlines in Figure 6(c) are not straight lines; this is due to turbulence in the flow.

Figure 7(a)–(c) illustrates the flow pattern around a narrow high-rise building in urban terrain (full-scale dimensions for tests in Figure 7(b) and (c): $L \times B \times H = 10 \times 80 \times 50\,\mathrm{m}^3$). In this case, the flow is mostly deflected

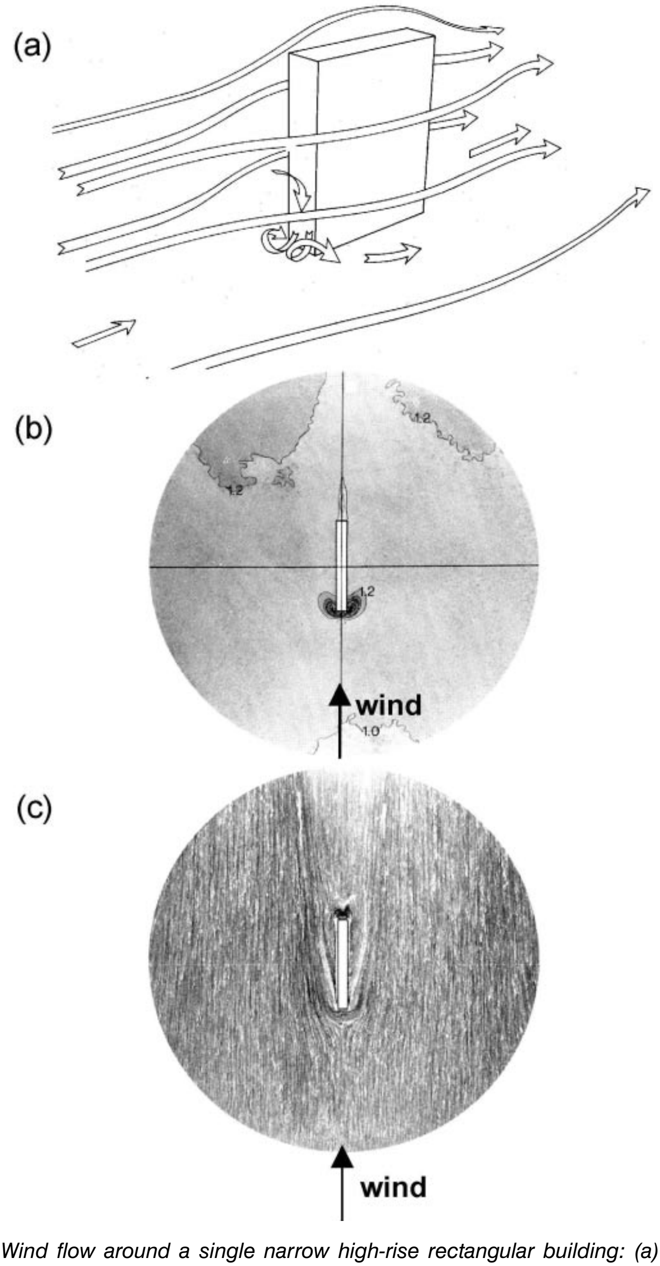

Figure 7. *Wind flow around a single narrow high-rise rectangular building: (a) schematic representation; (b) sand erosion contour plot; and (c) kaoline streak line plot obtained from wind tunnel tests on a building with full-scale dimensions* $L \times B \times H = 10 \times 80 \times 50\,m^3$ *[132] (reproduced with permission, © Kluwer).*

sideways due to the narrow windward facade. The standing vortex is hardly present and the flow rapidly resumes its normal direction (small influence area). The corner streams are small in area but high peak values appear to exist just downstream of the building corners.

Figure 8a–c illustrates the flow pattern around a wide and lower building in urban terrain (full-scale dimensions for the tests in Figure 8(b) and (c): $L \times B \times H = 160 \times 10 \times 35\,\mathrm{m}^3$). The flow mostly passes over the top of the building. Due to the small height, the standing vortex is limited and the stagnation point at ground level in front of the building is situated closer to the facade as compared to Figure 6. Nevertheless, the corner streams are high and extend a considerable distance downstream of the building.

Remark: From all figures, it is clear that the building significantly modifies the flow, downstream as well as upstream of the building. This is typical for subsonic flow.

In conclusion, the two most important wind flow zones at pedestrian level for single rectangular high-rise buildings are the standing vortex and the corner streams. Some important general guidelines can be extracted:

1. Building entrances near corners of especially high-rise buildings should be avoided, as well as walkways or bicycle routes. In addition to increased wind speeds, corner streams are also responsible for sudden wind direction changes. The direction of the corner streams in the immediate vicinity of the building corners is determined by the direction of the facade where the flow was attached to. This direction differs from the main flow direction. Therefore, surprising effects might occur, which can be dangerous or at least unpleasant for the inhabitants and the passers-by. Also doors and windows might suffer from these effects.
2. Recreational areas around high-rise buildings should be avoided unless specific attention will be given to the design of these areas – e.g. using a canopy to block the descending flow and the frontal vortex – where the effectiveness of the specific design features is to be ascertained by the use of wind tunnel or numerical modeling.

Wind Flow around Three High-rise Building Arrangements

This section discusses the wind flow around three specific building arrangements where typically problems of wind nuisance occur: (1) a building with a through-passage, (2) parallel buildings with a passage in between and (3) parallel buildings that are shifted towards each other. Sand erosion plots will be given for illustration. Where available, also streak line plots will be shown. This section concludes the literature review and provides the basis for examining the case studies in the next section.

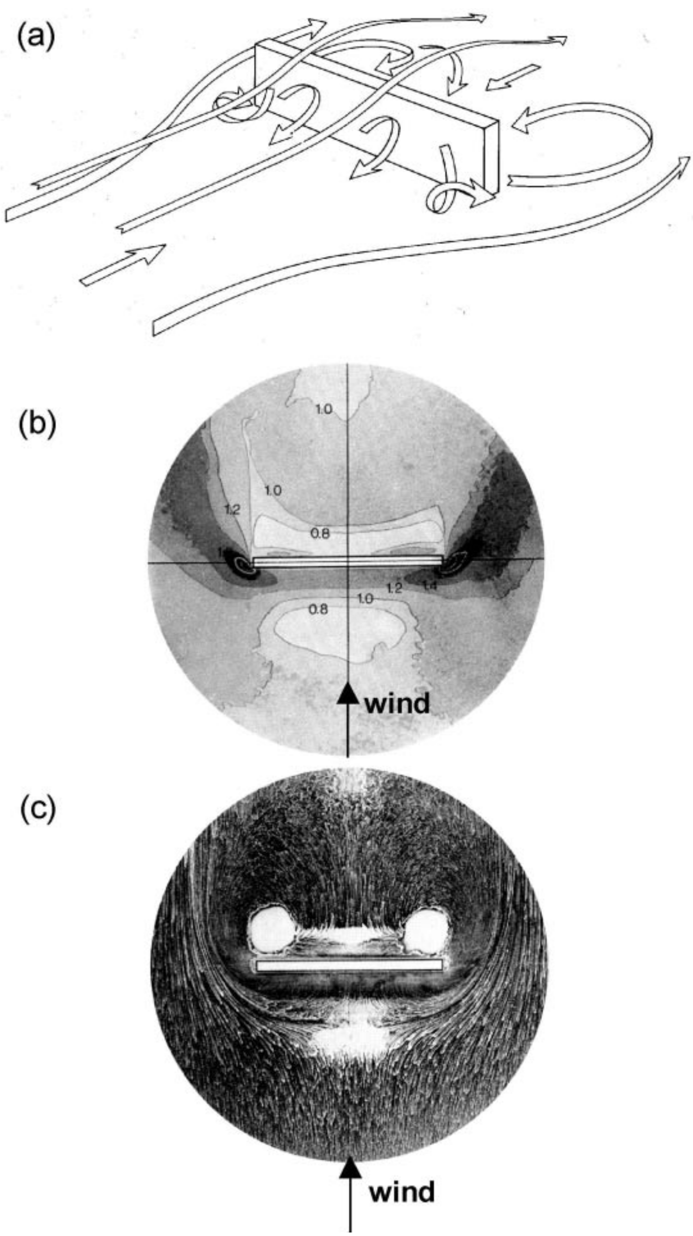

Figure 8. *Wind flow around a single wide and lower rectangular building: (a) schematic representation; (b) sand erosion contour plot; and (c) kaoline streak line plot obtained from wind tunnel tests on a building with full-scale dimensions* $L \times B \times H = 160 \times 10 \times 35\,m^3$ *[132] (reproduced with permission, © Kluwer).*

PASSAGE THROUGH A BUILDING

Through-passages or gaps in buildings are used to improve the accessibility between front and back facade and to conduct walkways and bicycle paths through buildings (Figure 9(a)). Because of pressure short-circuiting between windward (overpressure) and leeward (underpressure) facade (Figure 9(b)), wind conditions in building gaps are almost always unfavorable. Remark: corner streams in fact are also generated by a pressure short-circuiting effect, i.e. around the corners of the building. This is also indicated in Figure 9(b). Wind tunnel studies of flow in gaps have been reported by (in chronological order): Wise [75], Melbourne and Joubert [115], Wiren [130], Gandemer [104], Lawson and Penwarden [76] and Beranek [110,133,134]. Numerical studies have been performed by Bottema [66] and by Blocken et al. [72,73].

An example of the wind conditions around and under a building with a through-passage is given in Figure 10 (sand erosion contour plots).

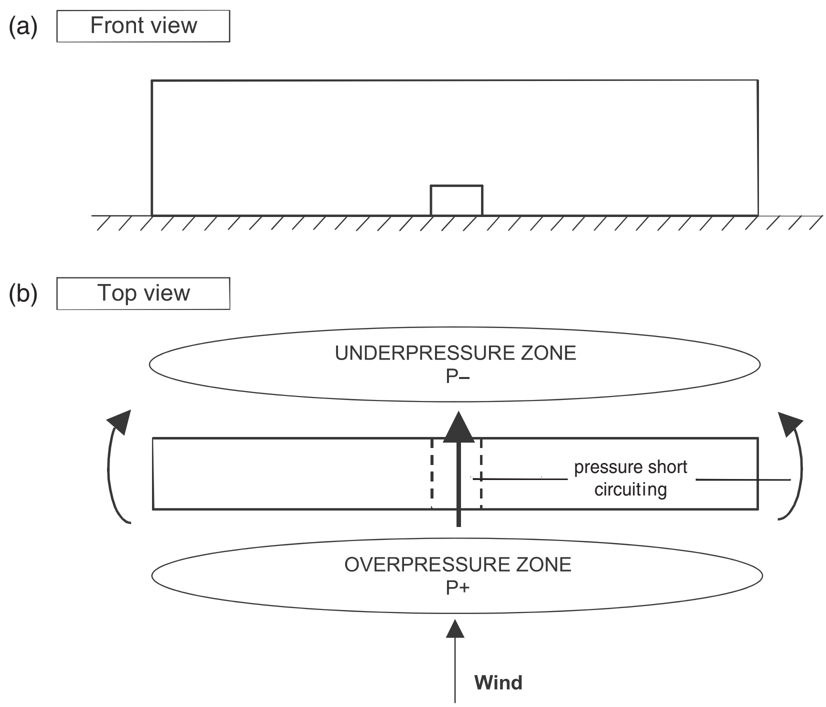

Figure 9. *Schematic representation of pedestrian level wind flow for a building with a through-passage. The flow through the passage is caused by pressure short-circuiting between windward (overpressure) and leeward (underpressure) facade. In fact, the corner streams are also caused by pressure short-circuiting.*

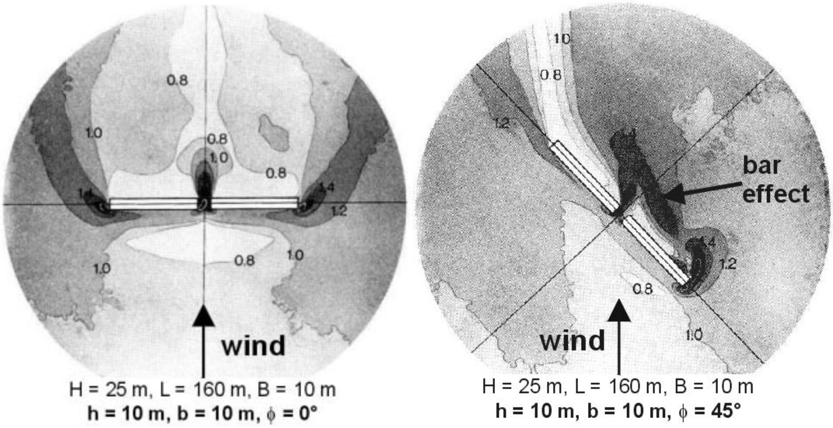

Figure 10. *Sand erosion contour plots illustrating the pedestrian level flow for a building with a through-passage. Building dimensions are* $L \times B \times H = 160 \times 10 \times 25\,m^3$*. The through-passage dimensions are* $b \times h = 10 \times 10\,m^2$*. Incident wind is 0° (left figure) and 45° (right figure). For 45°, the bar effect is observed [132] (reproduced with permission, © Kluwer).*

The building has full-scale dimensions $L \times B \times H = 160 \times 10 \times 25\,\text{m}^3$. The through-passage has a section $b \times h = 10 \times 10\,\text{m}^2$. Some of the general flow features found earlier are observed: the stagnation zone in front of the building and the corner streams. The standing vortex is hardly visible. Instead, a jet with firmly increased wind speeds is found in the passage and behind the building. The highest values are found just beyond the entrance (up to 1.8) but high values are clearly maintained for a considerable distance behind the building. The corner streams at the passage corners contribute to and merge into the passage jet. For oblique wind at 45°, the jet is situated at the left side of the passage. Corner streams are present at the upwind building corner and at the left passage corner. The one at the upwind building corner is more pronounced than that for wind direction 0°. This is confirmed by the numerical studies on rectangular buildings by Bottema [66] who concluded that in general corners streams for oblique wind are more severe. Measures to improve the wind climate in passages can be (1) the placing of screens in the passage to increase the flow resistance, (2) the use of long air-tight tubes ending outside the over– and underpressure zones to decrease the pressure difference or, (3) the simplest solution: to permanently close the passages. As through-passages in a building design can often be avoided, the latter solution is generally the best.

Remark: behind the building, the bar effect [104,110,134] is observed. It typically occurs for buildings (with or without through-passage) of moderate height (15–25 m) when the wind direction is about 45°. A vortex is formed that rolls over the building and that is more or less aligned with the building. It causes increased wind speeds at ground level. In the present case, amplification factors between 1.4 and 1.6 are observed.

PASSAGE BETWEEN PARALLEL BUILDINGS

As opposed to passages through buildings, passages between buildings are ubiquitous (Figure 11(a)). Especially for passages between high-rise buildings, wind conditions are often reported to be uncomfortable. Wind tunnel studies that specifically focused on the flow in passages between buildings have been reported by (in chronological order): Wiren [130], Beranek [133,134] and Stathopoulos and Storms [136]. Other wind tunnel studies of wind conditions in passages have been reported by Kenworthy [135], Jamieson et al. [151], Stathopoulos and Wu [137] and To and Lam [207]. Numerical studies have been performed by Bottema [66] and by Baskaran and Kashef [199].

Figure 12(a)–(d) provides sand erosion contour plots for building configurations with different passage widths: $t = 80$, 40, 20, and 10 m.

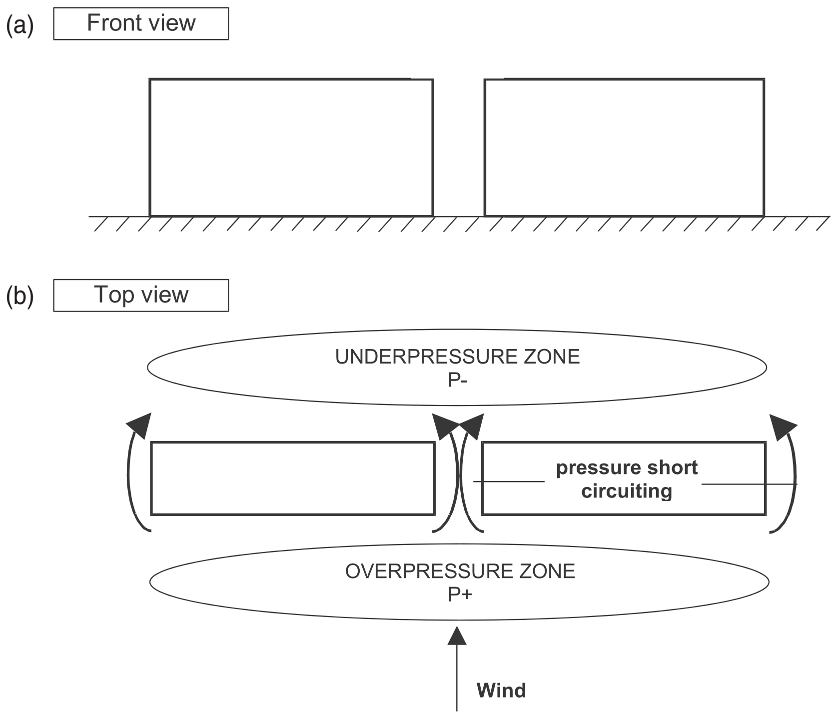

Figure 11. *Schematic representation of pedestrian level wind flow for two parallel buildings with a passage in between. Pressure short-circuiting between windward and leeward facade contributes to the flow between the buildings and the flow around the corners.*

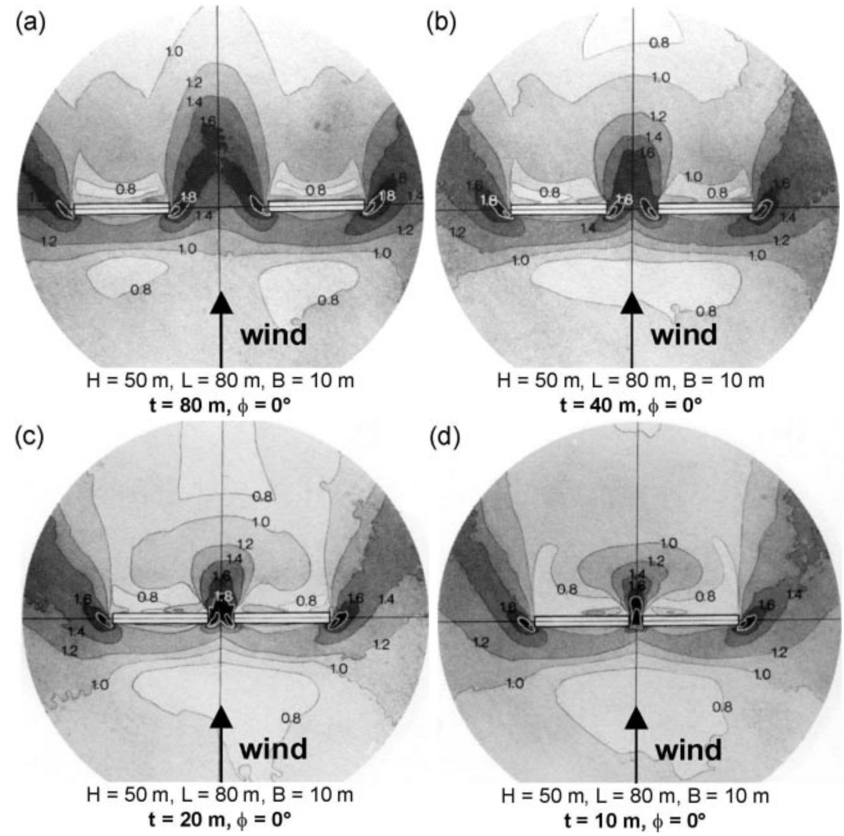

Figure 12. *Sand erosion contour plots illustrating the pedestrian level flow for two buildings with a passage in between. Building dimensions are as indicated in the figure. The passage width is (a) $t = 80$ m, (b) $t = 40$ m; (c) $t = 20$ m; (d) $t = 10$ m [133] (reproduced with permission, © Kluwer).*

In Figure 12(a), it can be seen that the buildings only slightly interact and that the wind flow behaves as it would do flowing around an isolated building. Two separate stagnation zones are present in front of the buildings and two separate standing vortices and separate corner streams are observed. As the buildings are moved closer together (Figure 12(b)–(d)) the interaction increases. The two stagnation zones merge into one large zone, the standing vortices interact and the corner streams in the passages merge into one single flow feature. Comparing these figures it appears that rather the opposite occurs of what one would expect: the areas where high local amplification factors occur decrease when the buildings are moved closer together (especially in the zone behind the building). Moreover, the peak values in the passages are hardly any more pronounced than those of a separate corner stream. This appears to be in contradiction to the experience of people that passages between buildings introduce increased wind speeds. It is the authors' opinion that passages between buildings (of the type given in Figure 11(a)) do not introduce increased wind speeds (as indeed shown by Figure 12) but that they do introduce the "experience" of increased wind speeds in the passage. By this we mean that in the case of Figure 12(a), people walking through the passage will tend to avoid the building corners and hence will not be subjected to the highest wind speeds. However as the passage width decreases (Figure 12(b)–(d)), the highest wind speed regions cannot be avoided by persons using the passage. So the increased wind speeds that are reported by people using passages between buildings are only due to the fact that these people are forced to move through the corner streams. A significant number of researchers have attributed the "increased" wind speeds in passages between buildings to the "Venturi effect" (i.e. the effect where wind speed increases as it passes through a smaller opening). This effect does not appear to be present, at least not for the building configurations given here. To our knowledge, the only researchers that have questioned the importance of the Venturi effect in pedestrian wind studies before are Beranek [133,134] and Bottema [66]. Further research is needed to find out if, when and to what extent the Venturi effect between buildings can be important. The fact that in the present configuration only corner streams are present is represented schematically in Figure 11(b).

SHIFTED PARALLEL BUILDINGS

Depending on the direction of the incident wind, shifted parallel buildings can give rise to severe pressure short-circuiting between the windward and the leeward facade, see Figure 13. Where possible, these arrangements should be avoided. Wind tunnel studies focusing on the flow around shifted buildings have been reported by Beranek [133,134]. Numerical studies have been performed by Bottema [66]. The sand erosion plot in Figure 14 illustrates that pressure short-circuiting can lead to large areas of very severe wind conditions (local amplification factor larger than 2.0). The streak line plot indicates that the local wind flow between the buildings remains parallel to the longitudinal facade for a considerable distance away from the building.

PRACTICAL EXAMPLES

Practical examples of buildings causing unfavorable pedestrian wind conditions are numerous. We have selected four cases that have been

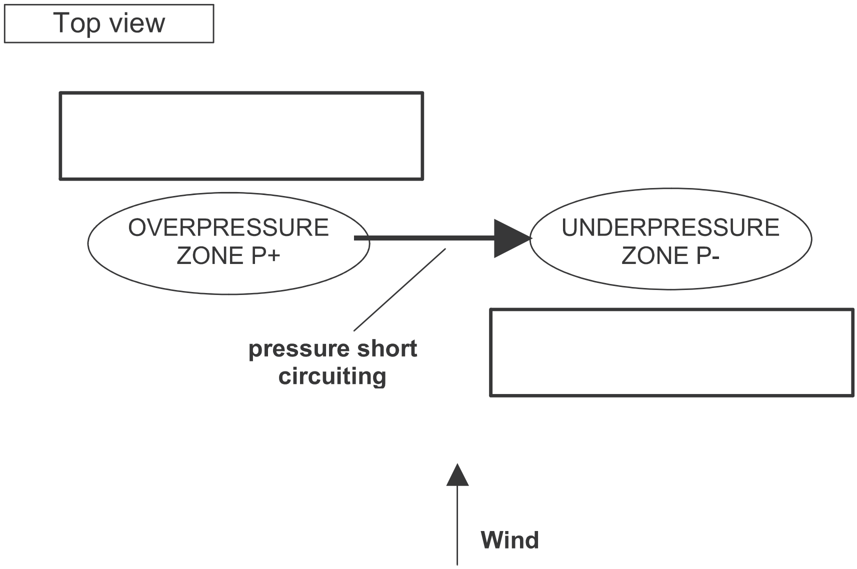

Figure 13. Schematic representation of wind flow for two parallel buildings shifted towards each other. The transverse flow between the buildings is caused by pressure short-circuiting between the overpressure zone in front of the windward facade of one building and the underpressure zone behind the leeward facade of the other.

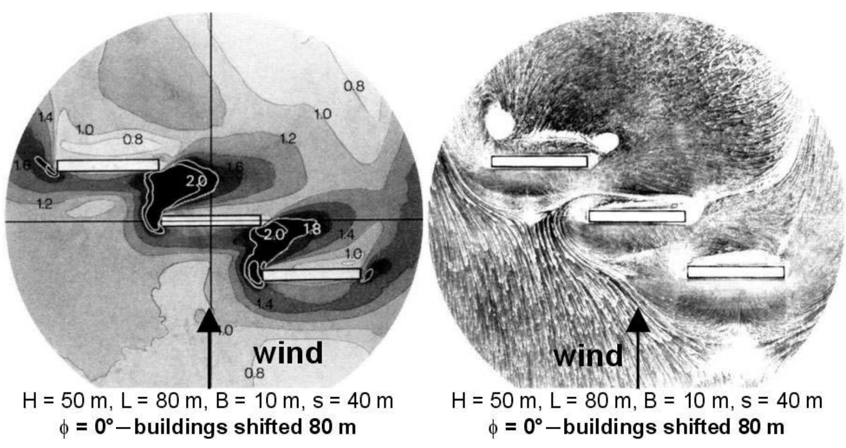

Figure 14. Sand erosion contour plot and kaolin streak line plot illustrating the pedestrian level flow for three parallel buildings that are shifted towards each other. Building dimensions are as indicated in the figure. The spacing between the buildings 's' is 40 m [133] (reproduced with permission, © Kluwer).

recently brought to the attention of the Laboratory of Building Physics, KULeuven. Three of the four cases have been studied with CFD modeling. Note that CFD modeling is only one of the two options for studying the pedestrian wind environment in detail, and that the other option (wind tunnel modeling) is also frequently used.

University Building 200D, Leuven

The campus "Arenberg III 200" of the Katholieke Universiteit Leuven (KULeuven) is situated on the outskirts of the city. A part of the buildings on campus is indicated in Figure 15. Building 200D is the highest building, measuring about $L \times B \times H = 90 \times 16 \times 25\,\mathrm{m}^3$. Since its completion in 1969, wind conditions around this building have been experienced as uncomfortable. Complaints have been received concerning the unpleasant wind environment both near the building corners (corner streams) and at the entrance of the building (high wind speeds near the door and over- or underpressure acting on the door). The entrance is located in the middle of the longitudinal facade. The number of complaints significantly rose after the construction of an additional building (Acoustics building) in 2001. This building with varying roof heights (the least of which is 7.5 m high) was positioned at a distance of 8 m from building 200D, creating a passage in between that was partly covered with a canopy. The passage length is about 30 m. Figure 16 illustrates the current situation. The building on the left is

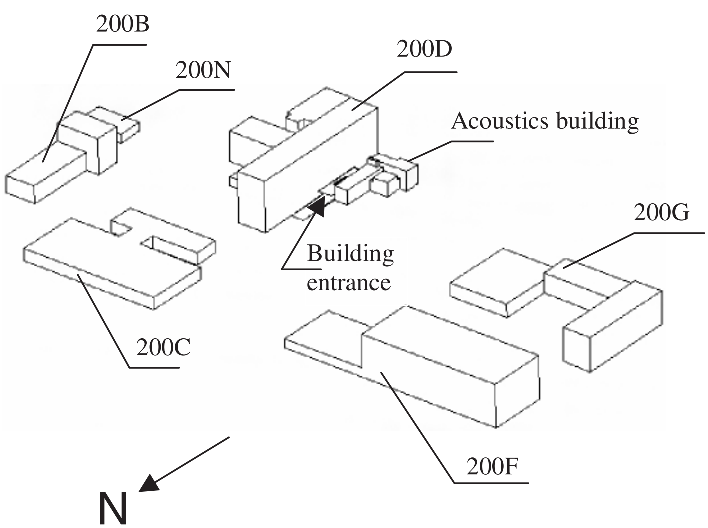

Figure 15. Perspective view of a part of the campus "Arenberg III, 200".

Figure 16. *Details of the passage between building 200D and the Acoustics building.*

200D, the building on the right is the Acoustics building. The photograph was taken in calm weather. Figure 17 illustrates the effort that is needed to open the entrance door in windy conditions. An inquiry indicated that some time ago, wind conditions have caused the doors to slam so hard that their glass shattered throughout the entrance hall. In order to avoid this, nowadays sometimes university technical staff is employed to gently open and close the door for the academic staff and the students. Strange enough, up to now, no steps towards an efficient solution have been taken. At the Laboratory of Building Physics, a CFD numerical study for this part of the university campus has been conducted [208]. Figure 18 illustrates local wind amplification factors in the passage and around building 200D for wind direction parallel to the longitudinal building facade. High wind amplification factors are found in the passage which are in clear contrast to the sheltered regions at the other side of the building. These would be a more suitable choice to position the building entrance. As for the present position, it is clear that closing one of the ends of the passage below the canopy (only one end is used to enter the building) and the canopy itself (which has an aperture in it) will drastically reduce the wind speed as through-flow will be inhibited. Over- and underpressure build-up over the door can be avoided by providing a permanent measure of pressure moderation.

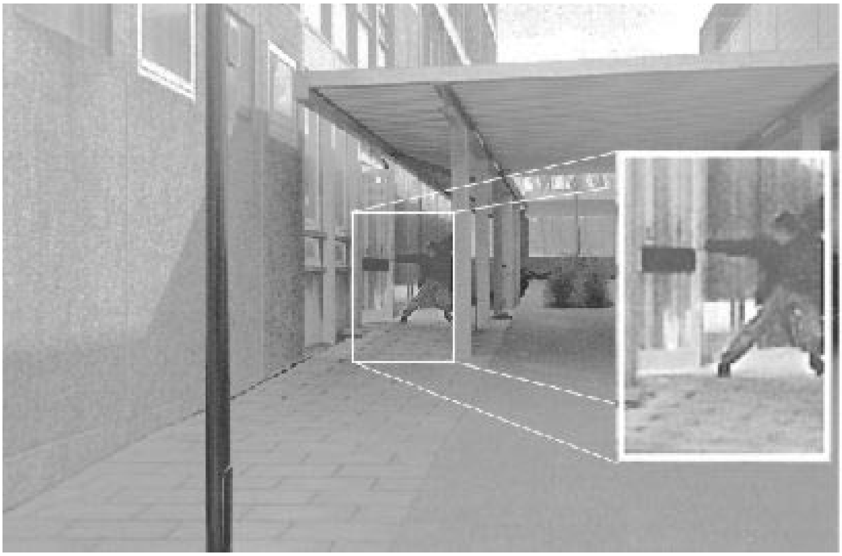

Figure 17. *Photograph illustrating wind nuisance, i.e. in this case the effort that is needed to open the entrance door in windy conditions.*

Figure 18. *Contours of local amplification factor for wind direction 0° (North) in a horizontal plane at 1.75 m height above ground (pedestrian height). High wind amplification factors are found in the passage which are in clear contrast to the sheltered regions at the other side of the building.*

Central Railway Station, Leuven

The prestigious project of the new Central Railway Station, including bus stops, was completed in 2001. It is situated just outside the center of the city. Figure 19 illustrates the newly built construction. The building is about 18 m high. Its main features are through-passages (visible in Figure 19) and a tunnel (not visible in Figure 19). The through-passages serve as platforms for passengers awaiting the bus. The tunnel connects the bus stop and the marketplace with the railway platforms. Because of pressure short-circuiting, unpleasant windy conditions almost always exist in the through-passages and in the tunnel. An easy solution cannot be provided here. It is not clear how the passages could have been avoided with the restriction of the current degree of intensive site exploitation.

The Silvertop Towers, Antwerp

The Silvertop Towers is a group of three high-rise (60 m) residential buildings located in the south of Antwerp (Belgium) near the Kiel Park.

Figure 19. *Photograph of the newly built part of Leuven Central Railway Station. The through-passages serve as platforms for passengers awaiting the bus.*

The towers were built in 1960. The decline of the towers and of the neighborhood has urged the housing department to initiate a comprehensive redevelopment project. An architectural contest was organized, in which the increase of public safety by social control (through sight) was given high priority by the jury. In the contest winning design, passages are constructed through each of the towers (Figures 20 and 21) with the main intention to increase the accessibility and to increase social control. The tower entrances are situated in the passages. Since the passages are the contest winning design feature, a favorable wind climate is imperative. Being aware of possible wind comfort problems, the designer asked the Laboratory of Building Physics, KULeuven, to assess the wind climate in the passages and, if needed, to suggest modifications restricted by the original design requirements. Therefore, CFD simulation of the wind flow around the Silvertop Towers and their surrounding buildings has been conducted [73]. The calculations indicate very high wind speeds in the passages (local amplification factors up to 3, see Figure 22) and the wind climate in the passages was assessed to be highly unacceptable. Various

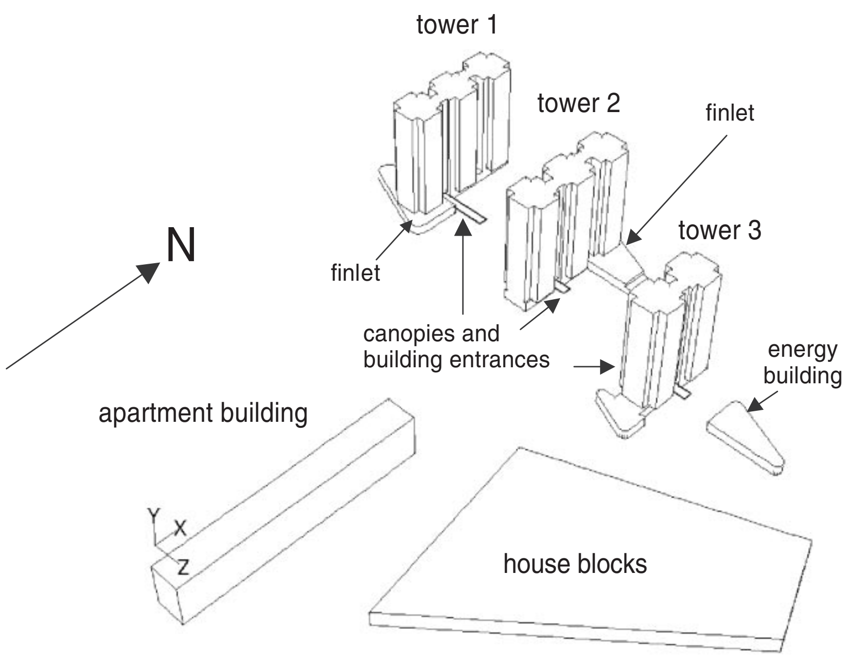

Figure 20. *Perspective view of the site of the Silvertop Towers – new design. The new design comprises through-passages and canopies through each of the towers. The building entrances are situated in the passages.*

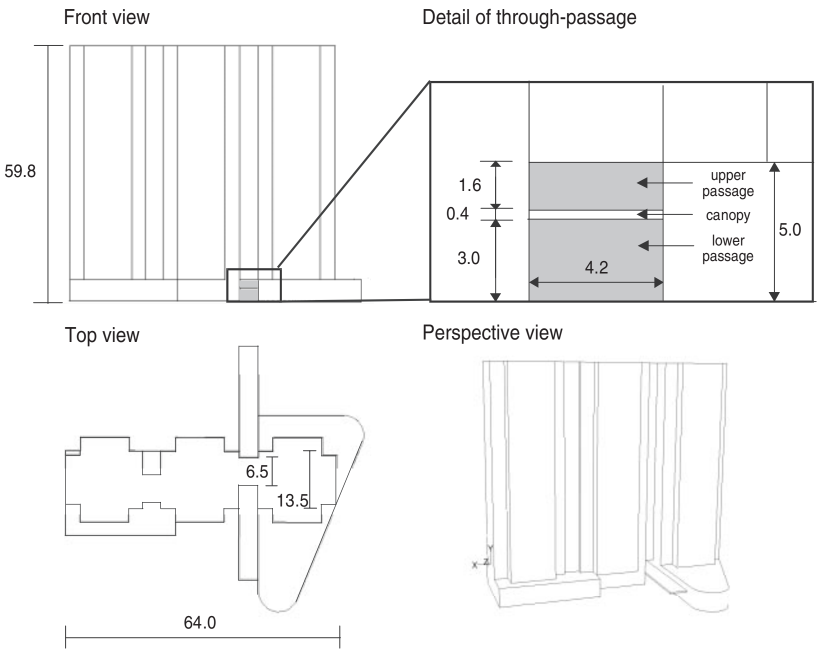

Figure 21. *Front view (from west) of tower 1 with detail of through-passage, top view and perspective view. The canopy divides the passage into two parts: an upper passage and a lower passage. (Dimensions are given in meter).*

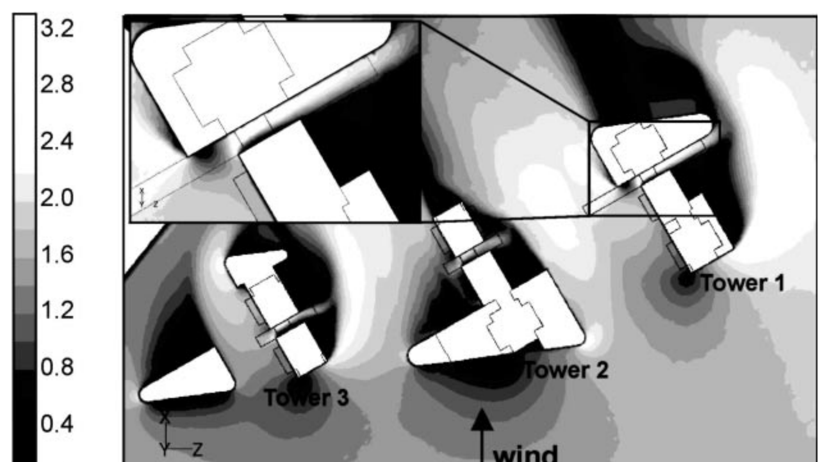

Figure 22. *Contours of local amplification factor for wind direction 30° in a horizontal plane at 1.75 m height above ground (pedestrian height). A detail is given of the conditions in the passage through tower 1, where the highest amplification factor is found.*

traditional remedial measures to improve the wind climate were contemplated, including (1) screens in the passage, (2) the extension of the passage with transparent tubes that end outside the over- and underpressure zones and (3) a revolving door in the passage. These solutions either provided an insufficient improvement of wind climate or conflicted with the envisaged architectural design. Therefore we finally selected a rather unconventional solution. We have designed and analyzed an automatic control system to modify the wind climate in the passages [73]. The actuators of the system are sliding doors that are mounted at both ends of the passage. The opening and closing of the doors is controlled by a decision algorithm based on local wind measurements. The wind measurements are performed in the upper passage that is always opened and has no other function in the design (Figure 21). At least one of the doors will be closed when the control system senses that the threshold wind speed in the passage is exceeded. The control system should ensure an adequate wind climate and does not conflict with the original architectural design. Full-scale validation tests will be conducted after building completion.

Joan Miro Residence, Genk

The attractive new high-rise residential building project "Joan Miro" in Genk (a city in the east of Belgium) has dimensions $L \times B \times H = 61 \times 22 \times 26\,\text{m}^3$ and consists of nine floors. At each floor, the apartments are accessible through the use of outdoor pedestrian platforms (Figure 23(a) and (b)). The platforms connect the individual apartments with the staircases and elevators (Figure 24(c)). The original design, made in 2002, consisted of four individual buildings (Figure 24(a)). With the possibility for wind nuisance in mind, the designer performed two important changes during the design process. The first design modification included the merging of the four buildings into two shifted, L-shaped buildings (Figure 24(b)). For the second design modification, the Laboratory of Building Physics was contacted and the joint conclusion of the first meeting was to additionally design a staircase in between both L-shaped buildings to avoid pressure short-circuiting between the shifted flats (Figure 24(c)). This was expected to significantly improve the wind climate. Nevertheless, a study of the pedestrian wind environment was requested in order for the building permit to be granted. A CFD numerical study has been performed at the Laboratory of Building Physics in an attempt to assess the wind climate. The study has indicated that both the first and the second design modifications were needed to ensure a favorable wind climate. Details of this study are provided in [209].

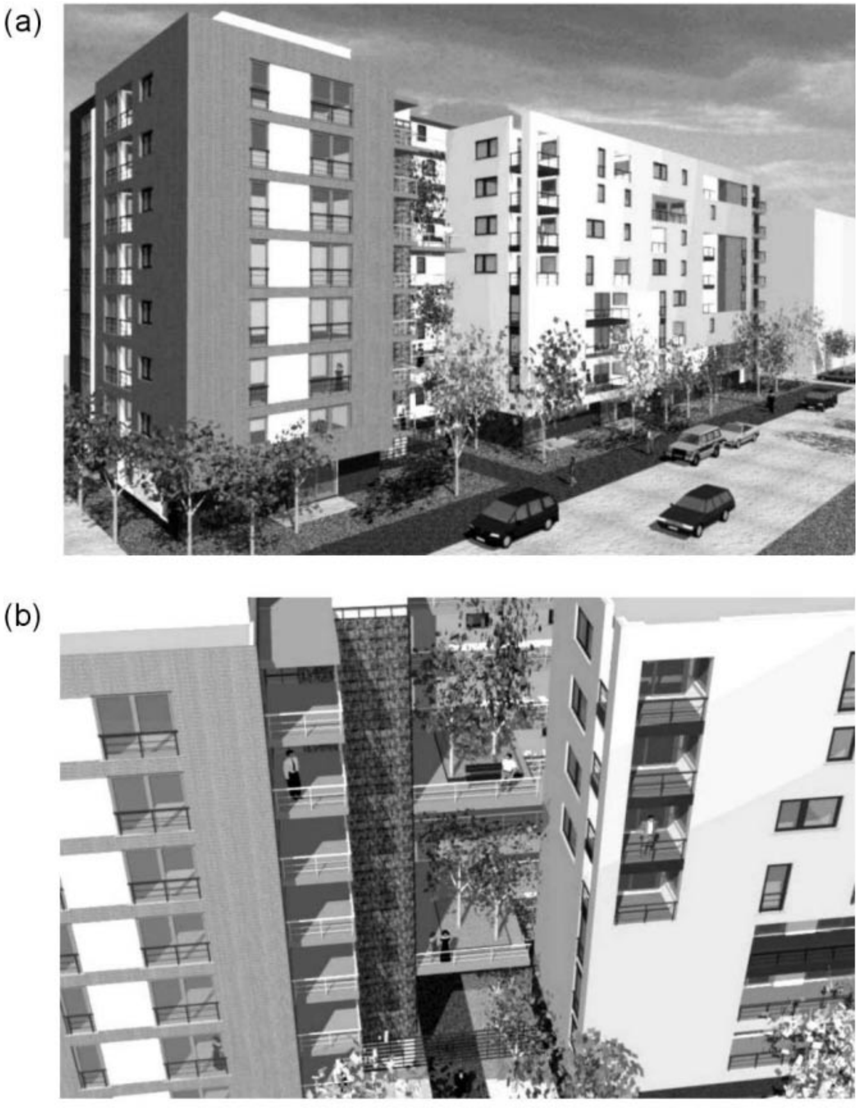

Figure 23. *Perspective view of the proposed design for residence "Joan Miro": (a) The building has dimensions* $L \times B \times H = 61 \times 22 \times 26\,m^3$ *and consists of nine floors; (b) At each floor, the apartments are accessible through the use of outdoor pedestrian platforms. The platforms connect the individual apartments with the staircases and elevators (reproduced with permission, © Herelixka and Claesen, 2003).*

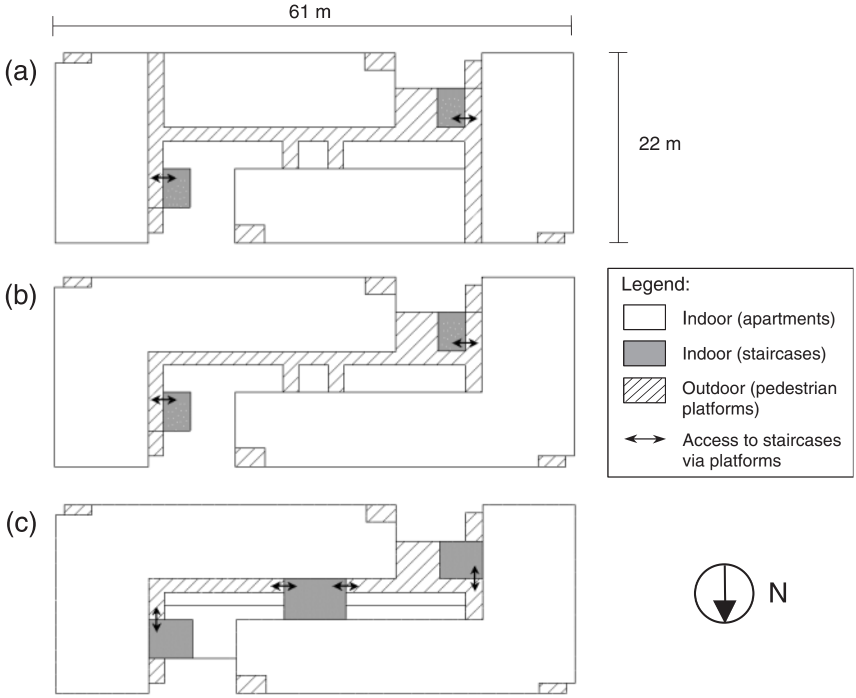

Figure 24. *View at the fifth level of residence Joan Miro. During the design, two times modifications have been made to improve the wind climate on the pedestrian platforms: (a) first design: four individual buildings of which two shifted buildings; (b) second design: two L-shaped buildings; and (c) third design: two L-shaped buildings with a staircase in between.*

CONCLUSIONS

- Knowledge of building aerodynamics is important in the design of a building from a Building Physics point of view. Especially the outdoor wind environment around buildings has received relatively little attention in the Building Physics community. The present paper has been an attempt (1) to stimulate the acquaintance with and the interest in this matter, (2) to indicate the need for additional research efforts and (3) to illustrate the need for inclusion of pedestrian wind studies in the design strategy of high-rise buildings.
- A review of the literature on pedestrian wind studies around buildings has been provided. The review is not pretended to be complete. Rather it is intended to present a starting basis including literature references to

stimulate further research. The following conclusions are drawn from the literature review:

1. The consequences of an unfavorable pedestrian wind environment near high-rise buildings can hardly be overestimated. High wind speeds can be detrimental to the success of new buildings. They can even be life threatening for the elderly and the infirm.
2. Past studies have indicated that for single rectangular high-rise buildings, the corner streams and the frontal vortex are the most important causes for wind nuisance.
3. Doors and passage-ways near buildings corners, passages through buildings and passage-ways that are led through narrow passages between buildings should be avoided because of pressure short-circuiting effects.
4. The same holds for shifted buildings.
5. The statement that passages between parallel buildings, placed side by side, introduce increased wind speeds – which is often called the Venturi effect – does not appear to be entirely true. It appears that the passage wind speed is hardly any more pronounced than the corner stream around a single building corner. At least for the examples given in this paper, no additional "effect" due to the passage itself is present.
6. There is an important lack of and an increasing demand for experimental data around a large number of building configurations to be used for CFD validation, in particular related to pedestrian wind. This is essential for the future use of CFD in pedestrian wind studies. When using CFD, the best that one can do at this moment is (1) to conduct the wind tunnel experiments oneself for the particular configuration under study (as done by example Bottema [64,65], Gadilhe et al. [154], Stathopoulos and Baskaran [155], Richards et al. [146], Ferreira et al. [147], Westbury et al. [148]), (2) to use the limited quantitative wind tunnel data that is available only for a few configurations (as done by for example, Baskaran and Kashef [199], Blocken et al. [72]), or (3) to use the qualitative database of wind tunnel studies provided by Beranek and Van Koten [132] and Beranek [110,133,134] (as done by e.g. Blocken et al. [72]).

- Four practical examples of recently designed buildings have been selected and briefly discussed. The conclusions are:

1. Most building designers are not sufficiently aware of possible wind environmental problems. Numerous examples exist of pedestrian wind nuisance in cities all over the world. Building designers that have knowledge of possible pedestrian wind problems for example, in Belgium, the designers of the Silvertop Towers and of Residence Joan Miro.

2. Solving a wind nuisance problem after the design has been finalized is difficult, expensive and often little effective. Therefore wind environmental conditions should be taken into account during and even before the design stage. But even then, combining an architectural design with considerations for an adequate wind climate is often difficult.

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