Wind and Comfort

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ABSTRACT

Wind plays always an important role in dealing with outdoor human comfort in an urban climate. Although various models of different complexity have been proposed to characterize the effect of wind on pedestrians in relation to their specific activities, it has been also recognized that human comfort in general may be affected by a wide range of additional parameters, including air temperature, relative humidity, solar radiation, air quality, clothing level, age, gender etc. 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. It is also noteworthy that there are significant differences among the criteria used by various countries and institutions to establish threshold values for tolerable or unacceptable wind conditions even if a single parameter, such as the wind speed is used as criterion. These differences range from the speed averaging period (mean or gust) and its probability of exceedance (frequency of occurrence) to the methodology of evaluation of its magnitude (experimental or computational). The paper attempts to review some of the work carried out in this area and to address some of the most recent efforts to develop wind ordinances, as well as to incorporate additional parameters in order to specify the threshold values or comfort ranges for respective weather parameters. Ideally, for design purposes, an approach towards the establishment of an overall comfort index taking into account wind conditions and other microclimatic factors should be an ultimate objective.
1. INTRODUCTION

Comfort in open urban spaces has received a lot of attention in recent years in 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, in response to significant interest expressed by the community, microclimatic conditions and particularly the effect of wind on the outdoor human comfort has been examined. Perhaps the American Society of Civil Engineers (ASCE) has put out a most pertinent state-of-the-art document (ASCE/SEI 2003), which was developed with input from the European Action C14. The latter, entitled Impact of Wind and Storm on City Life and Built Environment had a working group interested in the effects of wind on pedestrians, their assessment and comparisons, as well as the parameters they influence human comfort and its evaluation. Some of the results of this effort 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 Von Karman Institute for Fluid Dynamics in May 2004.

Furthermore, a 3-year EU-funded project carried out earlier in this decade with surveys at different open spaces complete approximately 10,000 interviews aiming to produce 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, psycho-physiological and sociological perspective of human comfort. A unique characteristic of this work consists of involving several aspects of physical environment (microclimate, thermal, visual and audial comfort, urban morphology) as well as social environment. The models and tools developed in the auspices of this project have been included in CRES (2004). The details of this project are available in http://alpha.cres.gr/ruros.

More recently, new criteria for the assessment of wind environment in cities in terms of ventilation performance and thermal comfort have been developed for several Asiatic countries, e.g. Hong Kong. Bu et al (2009) proposed two criteria for the evaluation of local wind environment, namely local air change rate and local kinetic energy.

The paper will describe the aerodynamics of the urban environment and the reasons causing high wind speeds at sidewalks and, consequently, potential discomfort to pedestrians; it will address both experimental and computational evaluations of the wind on people in the urban environment and will note the development of recent wind codes such as that in the Netherlands; finally, it will focus 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.

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 towards the street level due to the pressure differences created by the velocity differences between higher and lower levels. This downflow is significant due the pressure proportionality to the square of the velocity (Bernoulli equation) and its strength increases with the building height. This effect 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.

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 Figure 1. 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. Additional flow-induced mechanisms creating disturbances to the urban environment in the vicinity of buildings include but 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 re-circulation 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.

Figure 1: wind flow around buildings significantly taller than their surroundings, after Cochran (2004).

Common building configurations and potential influences on pedestrian-level winds are shown in Figure 2 taken from Cochran (2004). These configurations include the effects of canopies, which may act as deterrents to the strong down-flow prior to impacting on sidewalks or other pedestrian free access 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 adverse conditions on other places. An entrance alcove, as well as balconies on building facades, generally make sidewalk winds diminish. 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. This is a result of the so-called Venturi effect, which can be critical in some cases. However, recent work on the wind flow in passages between buildings (Blocken et al., 2008) has questioned the existence of the classical Venturi effect in such cases.
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 amongst them, particularly when the effect of ground topography and all adjacent buildings are 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. Only recently, more specifically during the last few years 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 this approach will be presented in a subsequent section.

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 Figure 3.

Figure 3: probability distributions of hourly mean wind speed at 300 m over Montreal for daylight hours during the winter (derived from 10 year record of wind data obtained at a height of 10 m at Trudeau Airport).

As clearly shown, westerly and southwesterly winds dominate while north and northeasterly 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 for west / southwest and, to a lesser extent from 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, architectural features such as setbacks, balconies and the like; the latter are ameliorated by alcoves, chamfered corners, landscaping (vegetation) or porous screens.
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 tolerable and unacceptable wind conditions even if a single parameter, such as the wind speed is used as 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 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. Jordan et al (2008) attempted to evaluate the response of a person to a sudden change in wind speed in terms of wind comfort and wind safety. It was found that the wind speed necessary to cause loss of balance was a function of the incumbent’s orientation and weight.

Table 1: Beaufort scale of winds as used on land, after ASCE (2003).

<table>
<thead>
<tr>
<th>Beaufort Number</th>
<th>Descriptive Term</th>
<th>Speed (km/h)</th>
<th>Specification for Estimating Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Calm</td>
<td>Less than 2</td>
<td>Smoke rises vertically.</td>
</tr>
<tr>
<td>1</td>
<td>Light Air</td>
<td>2 – 5</td>
<td>Direction of wind shown by smoke drift but not by wind vanes.</td>
</tr>
<tr>
<td>2</td>
<td>Light Breeze</td>
<td>6 – 11</td>
<td>Wind felt on face; leaves rustle; ordinary vane moved by wind.</td>
</tr>
<tr>
<td>3</td>
<td>Gentle Breeze</td>
<td>12 – 19</td>
<td>Leaves and small twigs in constant motion; wind extends light flag.</td>
</tr>
<tr>
<td>4</td>
<td>Moderate Breeze</td>
<td>20 – 29</td>
<td>Raises dust and loose paper; small branches are moved.</td>
</tr>
<tr>
<td>5</td>
<td>Fresh Breeze</td>
<td>30 – 39</td>
<td>Small trees in leaf begin to sway; crested wavelets form on inland waters.</td>
</tr>
<tr>
<td>6</td>
<td>Strong Breeze</td>
<td>40 – 50</td>
<td>Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.</td>
</tr>
<tr>
<td>7</td>
<td>Near Gale</td>
<td>51 – 61</td>
<td>Whole trees in motion; inconvenience felt in walking against the wind.</td>
</tr>
<tr>
<td>8</td>
<td>Gale</td>
<td>60 – 74</td>
<td>Breaks twigs off trees; generally impedes progress.</td>
</tr>
<tr>
<td>9</td>
<td>Strong Gale</td>
<td>75 – 87</td>
<td>Slight structural damage occurs e.g. to roofing shingles, TV antennae, etc.</td>
</tr>
<tr>
<td>10</td>
<td>Storm</td>
<td>88 – 102</td>
<td>Seldom experienced inland; trees uprooted; considerable structural damage occurs.</td>
</tr>
<tr>
<td>11</td>
<td>Violent Storm</td>
<td>103 – 116</td>
<td>Very rarely experienced; accompanied by widespread damage.</td>
</tr>
<tr>
<td>12</td>
<td>Hurricane</td>
<td>Above 116</td>
<td></td>
</tr>
</tbody>
</table>

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

- \( V = 5 \text{ m/s or } 18 \text{ km/h} \) onset of discomfort
- \( V = 10 \text{ m/s or } 36 \text{ km/h} \) definitely unpleasant
- \( V = 20 \text{ m/s or } 72 \text{ km/h} \) dangerous

**Conditions for pedestrians are considered acceptable if \( V > 5 \text{ m/s} \) less than 20% of the time**
Recognizing the importance of frequency of occurrence along with the magnitude of wind speeds, Figures 4, 5 and 6 provide threshold mean wind speeds for various types of activity as functions of the average annual number of storm occurrences. Naturally the mean wind speed threshold level drops significantly as the yearly average number of occurrences increases.

Utilization of mean wind speeds as comfort criteria for pedestrian-level winds has been questioned by the wind engineering community. In fact, the most prevailing opinion seeks an effective wind speed, which is related to the gustiness of the wind, to be used for that purpose. Such effective speeds can be derived from the following equation expressing their outcome in terms of the mean and a number (ranging from 1 to 3) of standard deviations of the wind speed:

$$V^e = \overline{V} \cdot (1 + \kappa \cdot \frac{\overline{V^2}^{1/2}}{V})$$

where:

$$\overline{V^2}^{1/2}$$ = rms of longitudinal velocity fluctuations

$$\kappa$$ = constant (≥ 1 to 3)

Figure 4: wind tunnel exposure of people at 10-15 km/h winds.

Figure 5: wind tunnel exposure of people at 20 (left) and 40 (right) km/h winds.
Wind tunnel experiments and observations of pedestrian performance suggest that $\kappa = 3$ is the most appropriate value. Figure 7 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 2.
Table 2: wind environment criteria of Murakami et al. (1986).

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>$\bar{U}_{\text{local}}$</th>
<th>$P(&gt;\bar{U}_{\text{local}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptable for walking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>summer:</td>
<td>48 km/h</td>
<td>0.01 (once per month)</td>
</tr>
<tr>
<td>winter:</td>
<td>32 km/h</td>
<td>0.01 (once per month)</td>
</tr>
<tr>
<td>Hazardous</td>
<td>83 km/h</td>
<td>0.001 (once per year)</td>
</tr>
</tbody>
</table>

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-sec gust speed will be roughly twice as large as the mean speed, he produced the curves shown in Figure 8. These curves identify threshold wind speed criteria for different types of activity similar to those shown in Table 3. 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.

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.

Table 3: wind environment criteria of Melbourne (1978).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Probability of Exceedance of ($P(&gt;U)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{U} = 36 \text{ km/h}$</td>
</tr>
<tr>
<td>Long-term and short-term stationary exposure</td>
<td>0.10</td>
</tr>
<tr>
<td>Strolling</td>
<td>0.22</td>
</tr>
<tr>
<td>Walking</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Wind ordinances in major cities**

There is great variation regarding wind ordinances in various cities / countries 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. Koss (2006) carried out a detailed analysis of different wind comfort criteria used at European wind engineering institutions. The study concluded that a code of good practice may be better based on criteria using hourly mean wind speeds. Furthermore, Sanz-Andres and Cuerva (2006) found that the differences in the comfort criteria used in various countries are due, to some extent, to the human perception or acclimatization considered in various countries.

In general, the following points can be made:

- Most major cities (Montreal, Toronto, Sydney, etc) have some guidelines addressing the problem at the approval stage for new construction projects. Montreal’s wind comfort criteria, specified in Article 39 of the *Cadre* (1992), refer to mean wind speeds rather than gust speeds. The critical mean wind speeds, $U_{\text{local}}$, for winter and summer are 14.4 km/h (4 m/s) and 21.6 km/h (6 m/s), respectively, and the maximum acceptable probabilities of exceeding these values are as follows:
Figure 8: probability distributions of Melbourne’s criteria for environmental wind conditions for daylight hours for a turbulence intensity of 30% and $\bar{u} = 2u$, after Melbourne (1978).
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.

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 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 a new wind ordinance has been approved in the Netherlands only recently after several years of intense efforts by several experts, architects and engineers. Table 4 summarizes the code criteria in terms of hourly averaged wind speed at pedestrian level. As an indicator of wind comfort, the code uses a threshold wind speed of 5 m/s; threshold for danger is 15 m/s. Grades of comfort are introduced related to the probability that a threshold wind speed is exceeded (Willemsen and Wisse, 2007).

Table 4: criteria for wind comfort and danger in NEN 8100, after Willemsen and Wisse (2007).

<table>
<thead>
<tr>
<th>Wind comfort</th>
<th>Activity area</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(V_{IS}&gt;5\text{m/s})$ in % hours per year</td>
<td>Grade</td>
</tr>
<tr>
<td>&lt; 2.5</td>
<td>A</td>
</tr>
<tr>
<td>2.5–5.0</td>
<td>B</td>
</tr>
<tr>
<td>5.0–10</td>
<td>C</td>
</tr>
<tr>
<td>10–20</td>
<td>D</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>E</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind danger</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(V_{IS}&gt;15\text{m/s})$</td>
</tr>
<tr>
<td>Dangerous</td>
</tr>
</tbody>
</table>

4. EXPERIMENTAL PROCEDURE: WIND TUNNEL APPROACH

As mentioned previously, the flows around buildings even in simple surrounding environments, let alone in complex urban settings are still extremely difficult to predict by computational methods. However, the testing of scale models in a boundary layer wind tunnel capable of simulating the mean-velocity profile and turbulence 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 set up of a wind-tunnel model in a boundary-layer wind tunnel is illustrated in Figure 9. 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 of 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 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 (1999). In typical wind tunnel tests, the airflow speed above the boundary layer is in the range 10 to 30 m/s.

![Figure 9: typical wind tunnel set-up for a pedestrian wind assessment study.](image)

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

The wind tunnel testing considers current conditions and those with the proposed development. Of course, 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.

5. COMPUTATIONAL PROCEDURE: CFD

In Computational Wind Engineering (CWE) the computer essentially replaces the physical simulation in the boundary layer wind tunnel, at least in principle. 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) 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).

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 recent computational studies for the evaluation of pedestrian level winds and the comparison of their results with respective experimental data are described in the following sub-section. 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. More details and specific comparison case studies can be found in Stathopoulos (2006).

Mochida and Lun (2008) carried out an excellent review of the CWE advances in the area of wind and thermal environment in Japan. The study suggested that CWE has grown from a tool for analysis to a tool for environmental design.

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 (2003). Furthermore, the studies by Nicolopoulou et al. (2001; 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 bio-meteorological 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 in this paper.

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 m/s = 4 mph) that would give the same rate of heat loss from exposed skin at 33°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).

**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 sun light absorbed and reflected by buildings need to be taken into account.

**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 attempted to work on 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 Figure 10 taken from 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.

![Figure 10: overall comfort example in terms of equivalent temperature difference, after Stathopoulos et al. (2004).](image-url)
Figure 10 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.

7. CONCLUDING REMARKS

This paper dealt with the aerodynamics of pedestrian level wind conditions, their experimental and computational assessment in the urban environment, as well as with the criteria used for outside human comfort in different parts of the world. Particular emphasis has been placed on the state-of-the-art and the current capabilities of Computational Wind Engineering to determine at least mean values of wind speeds in the vicinity of buildings in urban areas. An approach towards 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.

8. ACKNOWLEDGEMENT

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