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Pedestrian Wind Comfort in Large Cities

Agnieszka Kocoń*[1,2], Renata Kłaput[1], Aleksander Pistol[3], Agata Szeląg[1]

[1] Cracow University of Technology, Cracow, Poland
[2] Częstochowa University of Technology, Częstochowa, Poland
[3] Manchester Metropolitan University, Manchester, United Kingdom

Abstract. Despite the growing awareness of the issue of pedestrian wind comfort in urban areas, there is still little standardization in evaluating it. This paper presents the results of an extensive campaign comprising field measurements, surveys with local population and wind tunnel tests aimed at making the first step towards such a goal. The field measurements and surveys are conducted during different seasons (winter, spring, summer) at a particularly windy site in the city center of Warsaw, Poland, in the vicinity of several tall buildings. The total number of respondents who took part in the survey was 3 200. The analyzed area is then recreated in a model scale and tested at a wind tunnel facility. The obtained results are processed according to two existing criteria sets and are compared with field studies to provide an insight into some of the main factors contributing to pedestrian wind comfort: wind speed and the nature of the wind, air temperature and pedestrian activity. The conclusions show that the impact of air temperature and wind gustiness on pedestrian wind comfort seems larger than previously envisaged. Moreover, the research shows that low wind sensation occurs at low unsteady wind speed of around 3 m/s. The results of the research campaign provide better understanding of pedestrian wind comfort in the cities and support improved planning and design practices in urban environments.

Key words: urban planning, environmental impact on people, wind tunnel tests, field tests, survey studies

1. INTRODUCTION

The growing density of high-rise buildings in urban areas causes a change in the wind environment. This results in either too low (potentially causing stagnation of pollution [1]) or too high (resulting in uncomfortable or even dangerous wind conditions for people [2]) wind speeds at the pedestrian level in some areas. This paper focuses on the second case, i.e., increases in wind speed deteriorating pedestrian wind comfort. This problem should not be neglected as it may reduce the appeal of a given location and ultimately cause economic or social and economic disadvantages. Moreover, adverse wind conditions cause many complaints from urban residents and workers, having an impact on their mood and living conditions in large cities [3]. Due to the future urban development projects of the centers of large cities, the problem of deterioration of pedestrian wind comfort will likely exacerbate over the next years. Therefore, it is crucial to have appropriate tools to assess pedestrian wind comfort conditions and ultimately introduce solutions that improve local wind microclimate in the areas most affected by this problem [4]. Ensuring pedestrian wind comfort is essential for creating attractive and functional public spaces in rapidly growing urban centers.

Complex wind flow around buildings results from many factors, such as building shape [5], size, orientation with respect to the wind direction or interaction with the surroundings [6]. The methods commonly used to assess pedestrian wind comfort are wind tunnel tests [7] or numerical analyzes [8]; they enable also to predict wind conditions in future urban development projects. Field studies are another method to assess pedestrian wind comfort [9], which advantage is obtaining real wind conditions prevailing in the analyzed area; however its limitation is that it can be applied only in current state of urban development for limited subgroup of the population and current weather conditions, which limits the scope.

Different parameters influence pedestrian wind comfort, which is an individual feeling of each person: meteorological factors (wind speed, air temperature, solar radiation, humidity and precipitation), physiological factors (age, sex, physical activity, exposure time, clothing) and psychological factors (health condition, well-being, weather expectations) [10].

Another aspect which should be taken into account is that the assessment of wind comfort is strongly regionalized and depends on the geographic area [11]. The meteorological conditions in different countries or even in different regions within one country may vary significantly. Moreover, the social profile and so, the related features of people concerning the feeling of wind comfort and their weather expectations vary across different regions. Taking the above into account, the issue of pedestrian wind comfort should be analyzed holistically.

*e-mail: agnieszka.kocon@pcz.pl

Despite this complexity, many researchers elaborated different comfort criteria that may be used to evaluate pedestrian wind comfort: Isyumov and Davenport criteria [12], Lawson criteria [13], Melbourne criteria [14], NEN8100 criteria [15]. These criteria may be applied to the general population (thus they do not focus specifically on psychological factors) and are characteristic for particular regions. The research comparing wind comfort criteria based on a case study [11] clearly shows that wind comfort assessment can differ substantially when using different comfort criteria. The difference may be that these criteria were devised for different regions, hence for general populations of specific social profiles and specific weather expectations determined by their habitat. Perhaps the most comprehensive study on the topic of pedestrian comfort criteria is the COST Action C14 program whose results are summarized in [10] and in [16].

Comfort criteria assume that pedestrian wind comfort is mostly the effect of wind speed, exposition time and type of pedestrian activity, sometimes also accounting for the seasonality and thus, in a general way, for other weather parameters [11]. It is also assumed that comfortable wind conditions (wind speed lower than the threshold value) do not have to occur at all times – they should only occur often enough for comfortable use of the area in accordance with its intended purpose (the probability of exceedance of the threshold wind speed should be lower than the threshold value).

This paper presents a local analysis of pedestrian wind comfort around the complex of high-rise buildings located in the city center of Warsaw in Poland. Comprehensive elaboration of this problem was investigated during in-situ measurements and wind tunnel tests. Surveys concerning individual feeling of people about pedestrian wind comfort in a few areas were conducted. Meanwhile, the meteorological parameters (wind speed and air temperature) were measured at the site. During wind tunnel tests the model of the subject region of Warsaw was analyzed using two different wind comfort criteria. This research aimed to compare the results of pedestrian wind comfort assessment through previously established wind comfort criteria with sensations of wind comfort self-accounted by the local population, taking into account the corresponding measured weather conditions. Furthermore, the presented research serves as an initial study to develop wind comfort criteria suitable for cities in Poland – a vital task within the current prospect of rapid development of main cities in the country, which is transforming them into metropolises blooming with tall buildings. Up to now, there is no data available on this issue and the rather scarce works which evaluate wind comfort conditions around sites in Poland use criteria adopted from already existing ones from different regions.

Section 2 outlines the methods used in the field studies and wind tunnel tests. Section 3 presents the results obtained through both methods along with a comprehensive discussion and comparisons. The outcomes of the research are summarized in section 4.

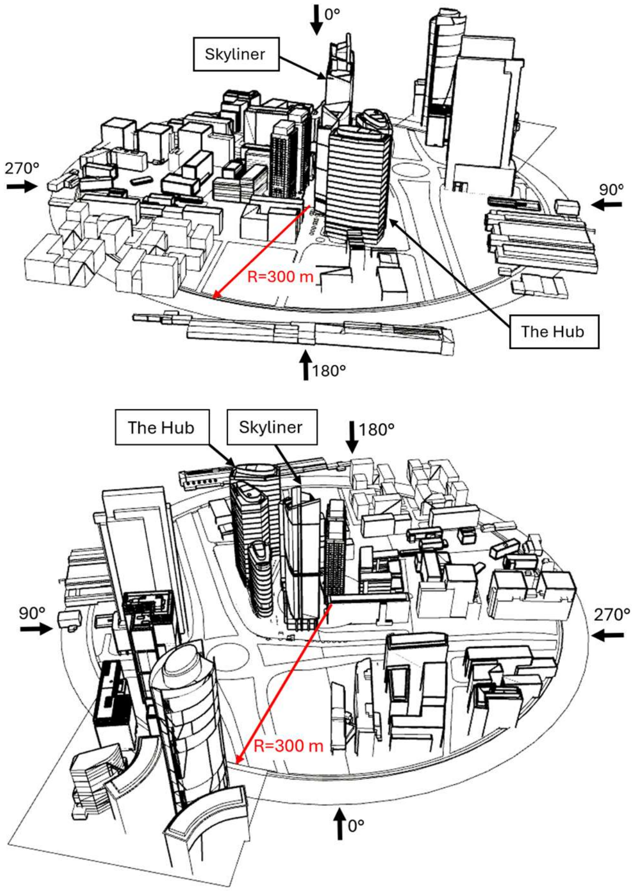

Fig.1. 3D schematic view of the measurement location (dimensions in real scale)

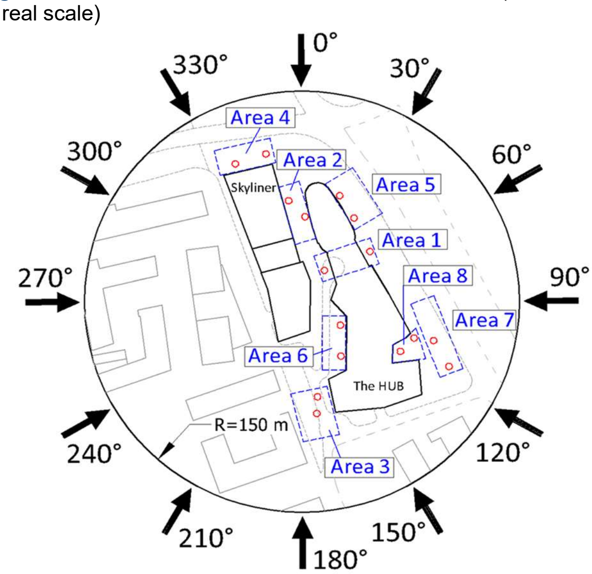

Fig.2. Location of the areas (marked in blue) and measurement points (marked in red) where pedestrian wind comfort was analyzed with respect to wind directions (dimension in real scale)

2. FUNDAMENTALS AND METHODS

2.1. Field measurements

Field measurements comprised the surveys with pedestrians about their self-assessment of wind comfort and measurements of weather parameters. The field measurements were conducted in the inner city center of Warsaw, Poland, around the complex of high-rise buildings. This location was chosen as this region of Warsaw is one of the most developed districts in the city and there was a notable deterioration of wind comfort conditions signalized in this particular area by developers and local communities. The 3D schematic of the measurement location is presented in Fig. 1; the city development is typical for highly urbanized city centers. The study was conducted within the vicinity of high-rise buildings: The Warsaw Hub (130 m) and Skyliner (195 m). The arrangement of the buildings in this location creates unfavorable wind conditions; there are several high-rise buildings in a limited area (comp. Fig. 1). All these factors combined suggest that problems with the wind environment in this area may gain even more importance in the future.

In-situ measurements were performed in eight areas illustrated in Fig. 2. These areas differ with respect to prevailing wind conditions and the type of usual pedestrian activity. The description and classification with respect to the usual type of pedestrian activity of the areas are summarized in Table 1.

TABLE 1. Description of areas and their classification with respect to the usual type of pedestrian activity

Area No.	Description	Usual type of pedestrian activity
1	passage on the ground floor allowing for free pedestrian communication	walking
2	the region between two high-rise buildings	rest/sitting
3	the region at the corner of the building	walking
4	pavement	walking
5	pavement	walking
6	recreation zone	rest/sitting
7	pavement between the trees	walking
8	building entrance	rest/sitting

Self-assessment of wind comfort by pedestrians was gathered separately in each of these areas. The interviewers asked pedestrians about the frequency of attending the area and their feeling of wind comfort (on the day of measurement/usually in this area). The questions in the survey and possible answers are listed in Table 2.

TABLE 2. Questions and answers in the survey concerning the self-assessment of pedestrian wind comfort

No.	Questions	Answers
1	How often do you frequent this area?	few times a week – every day
		few times a month
		occasionally (several times a year)
		never visited it before, this is the first time
2	How would you rate your sensation of wind comfort today in this area?	rating from 1 – the wind bothers me a lot, to 5 – the wind does not bother me at all
3	How would you rate your wind comfort usually prevailing in this area?	rating from 1 – the wind bothers me a lot, to 5 – the wind does not bother me at all

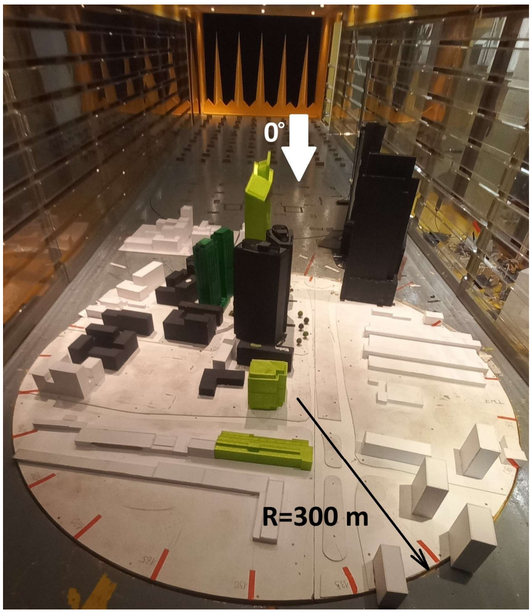

Fig.3. Measuring position in the wind unnel (dimension in real scale)

People who answered Question No. 1 that they were in this area for the first time were not asked to respond to Question No. 3. 3200 respondents answered Question No. 2 concerning today wind comfort while 2965 respondents answered Question No. 3 concerning usually prevailing wind comfort. Additionally, the interviewers noted the respondents' gender, age range, clothing (appropriate/inappropriate for the weather), well-being and temperature sensation, although these parameters were not analyzed in this paper.

The field measurements were conducted during daylight for 10 days throughout different seasons (2 days in February, 3 days in April, 2 days in May, 3 days in June), hence the analysis enclosed different weather conditions. The number of surveys for each area was either 25 or 50 per day; the total number of surveys was 3 200, 400 for each area.

Concurrently to the surveys, the measurements of weather parameters took place in the eight areas marked in Fig. 2. The weather parameters were measured usually through 15 minutes in one area and then the measurement location was changed to another area. The measurements were taken during collecting the surveys; however, not for the entire period of collecting the surveys in specific area.

HWS1000 Handheld Weather Station was used to measure wind speed, temperature, sun exposure level and air humidity, with the latter two not considered in this paper. The sampling frequency of these measurements was 1 Hz. The range of wind speed measurements was 0 to 40 m/s with the accuracy of 0.5m/s; the range of temperature measurements was -30°C to +70°C with the accuracy of ±0.3°C.

2.2. Wind tunnel tests

Wind tunnel tests to assess the wind comfort in the subject area were conducted at the boundary layer wind tunnel of the Wind Engineering Laboratory at the Cracow University of Technology. For more information on the facility, the Reader is directed to e.g. [17]. The closest surroundings of the analyzed high-rise buildings in a radius of 300 m were re-created in the scale of 1:300. The model scale (and thus the size of the area represented) was limited due to the dimensions of the working section of the wind tunnel and the scale of the flow characteristics possible to recreate. The model placed on the turntable is shown in Fig. 3. Measurements were carried out for twelve wind directions (with 0° indicating the geographical North), with a 30° angle increment (Fig. 2), three times for each wind direction. The sampling frequency was 250 Hz, while the measurement time was 30 seconds which corresponds to 2.5 hours in real-life scale. Biaxial hot-wire anemometers were used to obtain instantaneous wind speed at the pedestrian level adopted as 1.75 m in nature (about 6 mm in the model scale). Wind tunnel tests were conducted in 16 points; each area included two measurement points. Simultaneously, reference wind speed was measured at the reference height (z_{ref} = 42 cm in model scale) in an undisturbed flow in front of the model.

The measurements were taken in an area around the center of the model, but the wider surroundings were included to properly model their local effects on the flow conditions. The terrain category corresponding with the location of the subject area was simulated using the appropriate turbulence elements such as barriers, spires and blocks. It enabled to model the structure of the wind flow representing terrain category IV according to [18], which is characteristic for urban areas, with sufficient accuracy. The vertical profile of mean wind speed is presented in Fig. 4. The data for the power-law wind profile is provided, as it is the approach recommended in the Polish National Annex of the code [18].

Mean wind speeds at the pedestrian level and at the reference height were obtained from the measured time series. Based on this, wind speed amplification coefficient with respect to the wind direction (θ_i) was calculated for each measurement point and wind direction:

$$\gamma(\theta_i) = \bar{V}_P(\theta_i)/\bar{V}_{ref}(\theta_i). \qquad (1)$$

where: $\bar{V}_P(\theta_i)$ – mean wind speed at the pedestrian level at point P,

$\bar{V}_{ref}(\theta_i)$ – mean wind speed at the reference height.

These results were then used to calculate the probability of threshold wind speed exceedance [19]:

$$P_{exc}(\theta_i) = 100 \cdot P(\theta_i) \cdot$$

$$\exp\left[-(V_{TRH}/(\eta(\theta_i) \cdot \gamma(\theta_i) \cdot \beta(\theta_i) \cdot c(\theta_i)))^{k(\theta_i)}\right] \qquad (2)$$

where: V_{TRH} – threshold wind speed,

$P(\theta_i)$ – probability of wind direction θ_i (obtained from wind rose for specific region),

$c(\theta_i)$ – scale and $k(\theta_i)$ – shape parameter of Weibull distribution function,

$\eta(\theta_i)$ – time averaging coefficient,

$\gamma(\theta_i)$ – wind speed amplification coefficient,

$\beta(\theta_i)$ – transition coefficient.

Data from the meteorological station in Warsaw Okęcie used in these calculations (frequency wind rose and Weibull distribution parameters based on 10 min mean wind speeds)

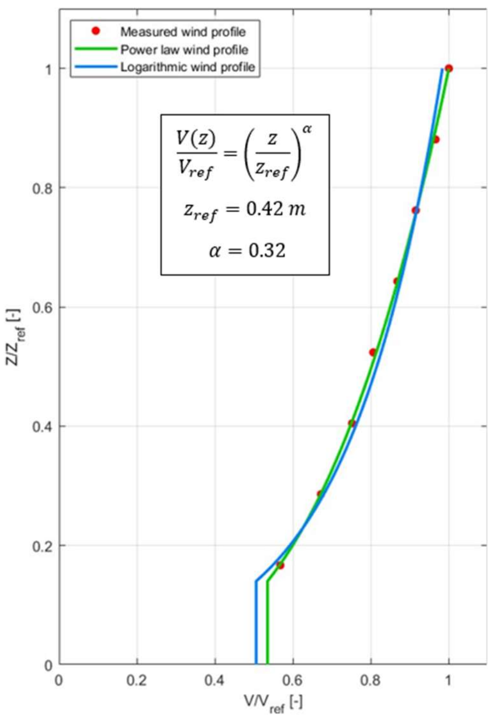

Fig.4. Mean wind speed profile

were obtained from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB, the main Polish body which gathers meteorological data and informs the public and organizations of atmospheric conditions). The distance between meteorological station and the measurement site was about 11 km.

Finally, the probability of exceedance of threshold wind speed (P_{TRH}) in each measurement point was calculated as the sum of probabilities for every wind direction ($P_{exc}(\theta_i)$). The obtained value of probability was used to assess the pedestrian wind comfort with respect to the two established comfort criteria: NEN 8100 criteria [15] (elaborated as part of the Dutch standard) and Lawson LDDC criteria [13] (adopted as a standard in the United Kingdom). The main purpose of adopting the above criteria is that they are based on different types of constant threshold values. NEN 8100 criteria are one of the newer sets; the constant threshold value adopted therein is the wind speed: V_{TRH} = 5 m/s. Levels of probability of wind speed exceedance (P_{TRH}) for different types of pedestrian activity are established for this threshold wind speed value. Four types of pedestrian activity are distinguished in the NEN 8100 criteria; they are presented in Table 3 along with their threshold values.

Table 3. Pedestrian wind comfort criteria of NEN 8100 [15]

Type of pedestrian activity	P_{TRH}
Sitting long	2.5 %
Sitting short	5 %
Walking leisurely	10%
Walking fast	20%
Uncomfortable	>20%

The constant value adopted in Lawson criteria is the probability of threshold wind speed exceedance: P_{TRH} = 5%.

Table 4. Pedestrian wind comfort criteria of Lawson LDDC [13]

Type of pedestrian activity	V_{TRH}
Frequent Sitting	2 m/s
Occasional Sitting	4 m/s
Standing	6 m/s
Walking	8 m/s
Business Walking	10 m/s
Uncomfortable	>10 m/s

Levels of wind speed (V_{TRH}) for different pedestrian activities are established for this threshold probability. Five types of pedestrian activity are adopted in Lawson criteria; they are presented in Table 4 together with their respective threshold values. So far, a variety of Lawson criteria have been elaborated; in this paper, the LDDC (*London Docklands Development Corporation)* variant was used.

It should be noted that by default, the Lawson criteria take into account gust velocities – either GEM (gust equivalent mean) or maximal moving average from a period of 3 seconds, which would result in significantly larger values of the wind speed amplification coefficients. However, for the sake of consistency with the other methods employed (NEN 8100 and field measurements), it was decided to use the mean wind speed.

3. RESULTS AND DISCUSSION

3.1. Results of field measurements

Results of field surveys concerning the assessment of wind comfort by pedestrians for the eight areas are presented in Figs. 5 and 6. Two separate charts concerning the self-assessed rating of Today's Wind Comfort (TWC – Question No. 2 as per Table 2) and Usually Prevailing Wind Comfort (UPWC – Question No. 3) are provided. The results of all the surveys from 10 days of field measurements are cumulated in these charts, taking into account the percentage of each answer (rating in the range of 1 to 5) of respondents.

It was assumed that the respective rating represents the following feeling of self-assessed wind comfort: 1 – very uncomfortable, 2 – uncomfortable, 3 – moderately comfortable, 4 – comfortable and 5 – very comfortable.

Analysis of variance ANOVA was performed to examine data distribution. The significance value was calculated taking into account the whole range of data concerning usually prevailing wind comfort results (UPWC) for each area separately considering five subgroups of different range of age. For the areas in which significance level indicated that differences between results in some subgroups may appear post hoc tests were conducted. For 6 of 8 areas no significant differences between subgroups were indicated. For remaining 2 areas lower significance value may result from smaller amount of data collected for one of two groups where the lower significance value was obtained.

Assessment of TWC shows that each area is rated differently. Considering the rating of the majority of respondents, they assessed wind comfort in areas: 1, 2 and 3 at least at 3

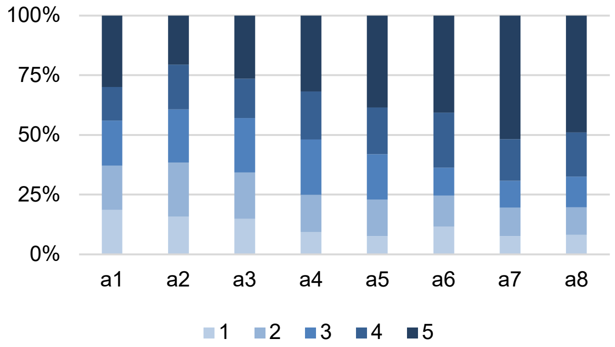

Fig.5. The assessment of today wind comfort (TWC) according to field surveys

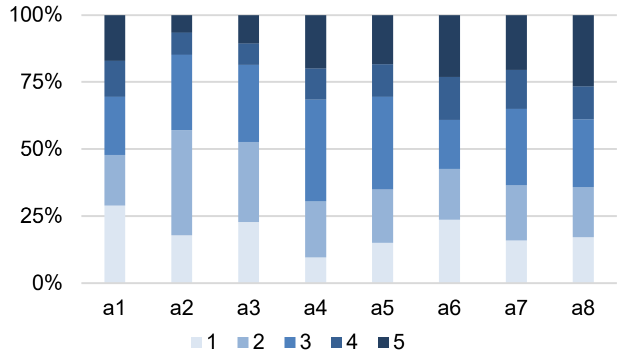

Fig.6. The assessment of pedestrian wind comfort prevailing usually (UPWC) according to field surveys

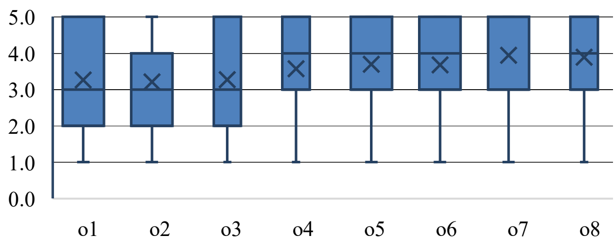

Fig.7. Data distribution of the assessment of today wind comfort (TWC) (used symbols: cross – average, horizontal line – median, box plot – data between 25th and 75th percentile, whisker plot – data between 5th and 95th percentile)

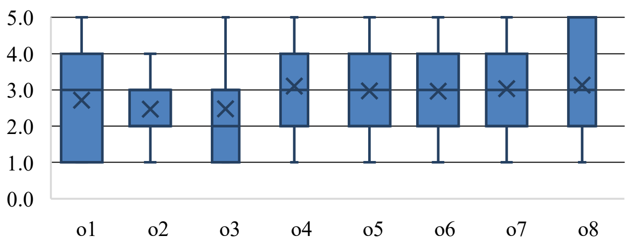

Fig.8. Data distribution of the assessment of pedestrian wind comfort prevailing usually (UPWC) (used symbols: cross – average, horizontal line – median, box plot – data between 25th and 75th percentile, whisker plot – data between 5th and 95th percentile)

(moderately comfortable); in areas: 4, 5, 6 and 8 at least at 4 (comfortable) and in area 7 at 5 (very comfortable).

The results from the UPWC assessment are quite different. The majority of respondents assessed wind comfort in areas: 2 and 3 at least at 2 (uncomfortable); in areas: 1, 4, 5, 6, 7 and 8 at least at 3 (moderately comfortable). These results were significantly different from the results obtained for the TWC assessment. Perhaps unsurprisingly, it can be concluded that over a longer time, people tend to evaluate the wind comfort conditions as more “moderate”, i.e. at around 3. On the other hand, in the TWC assessment, the potential incidental better or worse conditions on the day lead to more answers on either side of the spectrum.

For detailed evaluation of the survey results data distribution concerning the ratings of TWC and UPWC was presented in Fig. 7 and Fig. 8, respectively. Average rating as well as median and values between first and third quartile together with values of 5th and 95th percentile were presented. As the main observation which was already indicated is that results of TWC are generally higher than those of UPWC which is demonstrated by the average rating and the range of ratings between first and third quartiles. Furthermore, the data between 5th and 95th percentile encompasses the entire rating scale for nearly all areas thereby showing significant variation in respondents sensation of wind. It is evident that during 10 days of measurements, when different atmospheric conditions prevail, people could assess wind comfort in the whole range of rating, hence the bias in TWC is obvious. Nevertheless, for UPWC such variability in responses proves that wind sensation is subjective. Consequently, in order to evaluate wind comfort for population it is necessary to implement an averaging process.

As the results of TWC and UPWC differ noticeably it indicates that people rated wind comfort which they experienced at the moment of measurement at different score than wind comfort which they usually experienced in this specific area. Therefore, it may be concluded that people are able to distinguish between wind conditions that they experience during one specific day and wind conditions that they experience most of the time in a given area. It proves the assumption in already existing comfort criteria based on threshold wind speed [15] and probability of exceedance [13]. According to them people feel discomfort at a certain threshold wind speed hence they state that the wind bothers them at the specific time when this speed is exceeded. However, if the probability of exceeding the threshold wind speed is fairly low the overall wind comfort remains acceptable, as people state that the wind conditions do not bother them most of the time.

During field tests, the weather parameters were measured as well. Figures 9 and 10 show the relationships of TWC ratings to air temperature and wind speed for 10 days of measurements. The charts present the rating of the majority of respondents in each area, e.g., if an area is rated at 3, it means that the majority (more than 50%) of respondents rated wind comfort at 3 or above. Two sets of charts are presented: the first set shows the TWC rating with respect to air temperature – maximal and minimal – measured during the survey, with

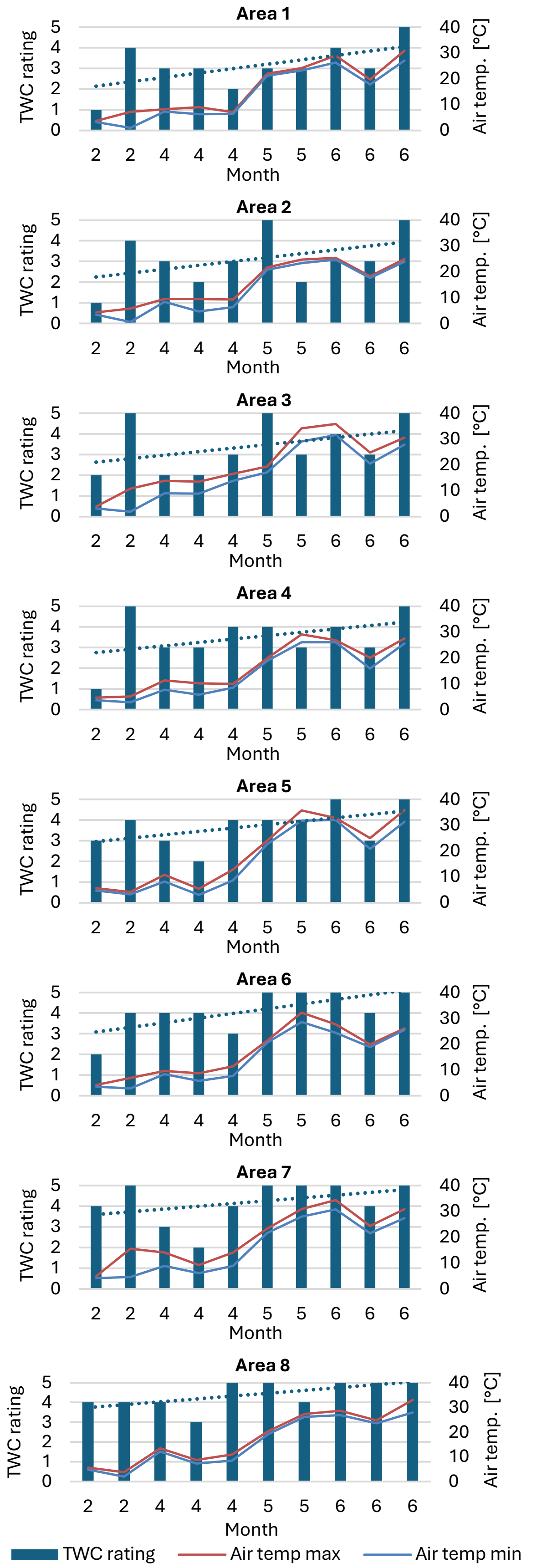

Fig.9. Relationship between TWC rating and air temperature with respect to month (2 – February, 4 – April, 5 – May, 6 – June)

a trend line marked for the TWC rating. The second set shows the TWC rating with respect to mean and gust (maximal) wind speed.

The trend line for the TWC rating shows a general improvement in wind comfort over the course of measurement days (spread across 3 different seasons from winter to summer) which is, naturally, coincident with a general increase in air temperature. A slight decrease in air temperature on the 2nd day of measurements in June is also represented in worse self-assessment of TWC observed for almost all areas except area 8 (a nearly no-windy area) highly rated by respondents. Moreover, local small changes in air temperature are observed for some areas, which is also reflected in worse today wind comfort rating for the 2nd day of measurements in April for areas: 2, 5, 7 and 8. The results clearly show the positive influence of higher air temperature on wind comfort experienced by people, suggesting there should be a stronger emphasis on including this factor, thus far either omitted or considered rather briefly, in the wind comfort criteria. This observation is consistent with the assumptions made in NEN 8100 comfort criteria [15] which allow for the adoption of two threshold values of wind speed – 4 m/s for lower air temperatures (winter) and 6 m/s for higher air temperatures (summer).

Analyzing the results of TWC with respect to wind speed, more local changes are observed (Fig. 10). Wind speed varied significantly for different areas which is also represented in the TWC rating. High wind speeds in combination with low air temperature on the 1st day of measurement in February caused a low rating of TWC in most of the areas. The effect of wind speed on TWC is also clearly seen when comparing wind speeds on the 1st and 2nd day of measurement in February. Even if the air temperature did not increase much (in some areas even decreased), wind speed decreased significantly which is reflected in higher TWC rating for the 2nd than for the 1st day of measurement in February. This suggests that at lower temperatures people are more vulnerable to wind action and high wind speeds significantly decrease their self-assessment of wind comfort. It is worth to point out that according to IMGW (Institute of Meteorology and Water Management) the strongest winds (above 10 m/s) appear in Warsaw during the winter, which additionally enhances the importance of low air temperature influence on pedestrian wind comfort. At higher air temperatures, people's demands in regard to accepted wind speed were generally lower; hence for higher air temperatures wind comfort was assessed similarly as for lower air temperatures even if wind speed was higher, e.g. comp. measurements from 1st day in April and 1st day in June in area 2; 1st day in April and 2nd day in June in areas 3, 5 and 6; 2nd day in February and 2nd day in May in areas 7 and 8.

Both daily mean and gust wind speeds measured throughout measurements present peaks and decreases. It is noteworthy that the decreases in wind speed for consecutive days of measurements (i.e. in the events when the measurements were done in a direct day-to-day succession) are mostly reflected in the TWC rating. The rating was higher when wind speed

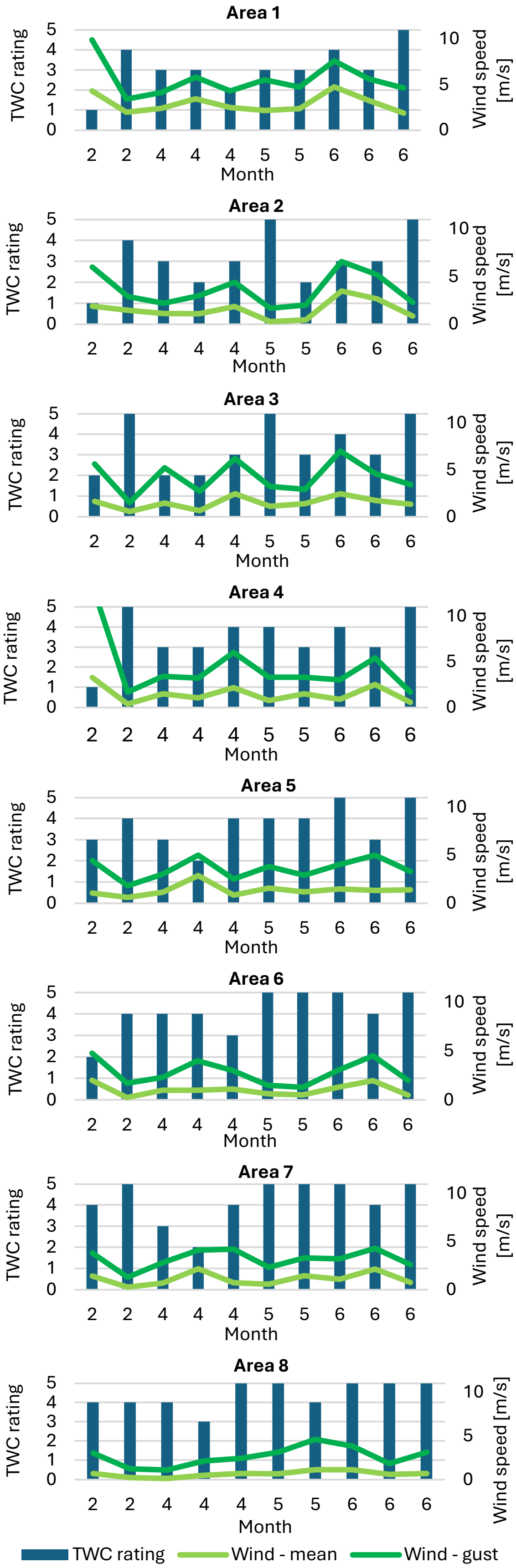

Fig.10. Relationship between TWC rating and wind speed with respect to month (2 – February, 4 – April, 5 – May, 6 – June)

decreased over the previous day. This trend is observed for the measurements conducted on 1st day in May and 3rd day in June for most of the areas. However, air temperature increment was also observed for these days, hence both (higher air temperature, lower wind speed) could be a reason for better wind comfort self-assessment. Nevertheless, the direct and instantaneous reaction for improved weather conditions, even if difficult in practical implementation for pedestrian wind comfort assessment, is potentially another strong factor contributing to the sensation of wind comfort.

At this stage, it is worth mentioning the remarks of some respondents which were mainly reported on warm days (measurements on 3rd day in May, 1st and 3rd day in June). People noticed that during the hot days, wind is desirable and sometimes complained that wind speed was too weak. This remark was reported in results for areas 1, 2 and 3 for the 1st day of measurement in June, where the wind speed was higher than in the previous and next measurement days. The same trend is observed for air temperature. Even if the wind speed was higher, the rating of TWC was better (or the same) than in the previous and next measurement days. It might lead to the conclusion that at higher air temperatures wind action has a cooling effect on people, hence wind speed that causes discomfort is higher than in days of mild temperatures and might require a different approach to evaluate.

3.2. Results of wind tunnel tests

Wind tunnel tests allowed to assess pedestrian wind comfort using two comfort criteria sets described in subsection 2.2: NEN 8100 criteria and Lawson criteria. Results of wind tunnel tests were compared with survey results of pedestrian wind comfort prevailing usually (UPWC) as people were able to distinguish instant and prevailing wind conditions in the same area. The comparison is presented in Figs. 11 and 12 for each of the areas. The results of field surveys are presented in the form of bar chart indicating percentage of answers that received specific rating in each area. The results of wind tunnel tests are presented as colored dots (two measurement points in every area) determining the type of pedestrian activity that is comfortable in specific areas according to NEN 8100 criteria (fig. 11) or Lawson criteria (fig. 12). Furthermore, the most prevalent type of pedestrian activity in specific areas was hatched in order to analyze whether the specific region fulfils its function taking into account results of field measurements and wind tunnel tests.

To better interpret the comparison, the results were summarized in chart form in Fig. 13. The bar chart presents the pedestrian wind comfort in each area for wind tunnel tests results averaged from two measurement points and assessed according to NEN 8100 criteria (defined as NEN in Fig. 13) and Lawson criteria (defined as Lawson in Fig. 13). Moreover, the usual type of pedestrian activity in specific areas was presented – areas where people are used to walk through (defined in figs. 11 and 12 as walking) should at least meet comfort criterion for fast walking while areas where people are used to sit or rest (defined in figs. 11 and 12 as sitting) should at least meet comfort criterion on sitting short

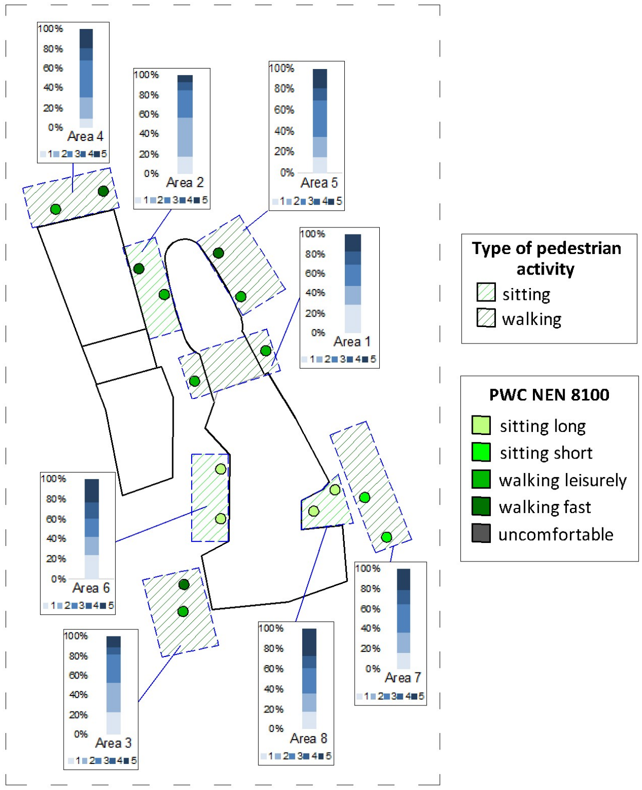

Fig.11. Results of field surveys (bar chart) and wind tunnel tests (colored dots) using NEN 8100 criteria with usual types of pedestrian activities (hatched) in respective areas

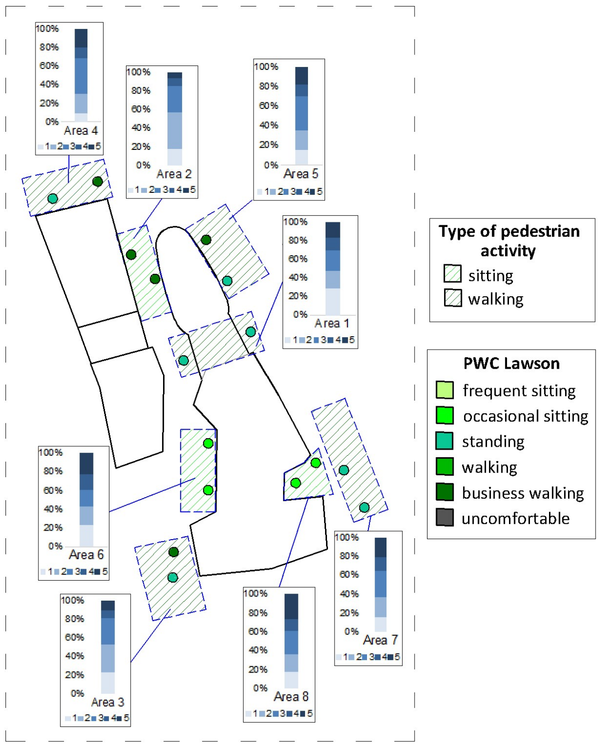

Fig.12. Results of field surveys (bar chart) and wind tunnel tests (colored dots) using Lawson criteria with usual types of pedestrian activities (hatched) in respective areas

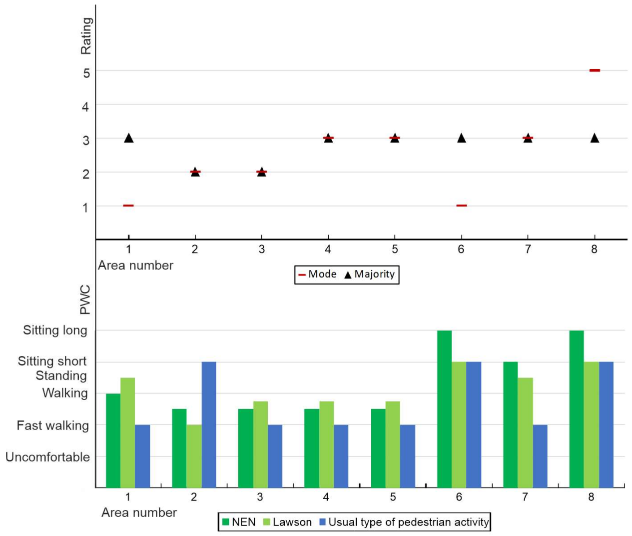

Fig.13. Comparison of pedestrian wind comfort rating from field surveys (point chart) and wind tunnel tests (bar chart) using NEN 8100 comfort criteria (NEN) and Lawson criteria (Lawson)

as it is illustrated in fig. 13. Above the bar chart, two types of results from field surveys are compared: the rating which was most commonly indicated by respondents (mode) and the rating which represents that the majority of respondents rated wind comfort at that value or above (majority).
The results show that mode is in many cases the same as the majority. However, in areas 1 and 6 the mode is two points lower than the majority, which might suggest a result bias in these areas (disproportionately high number of 'extreme' answers). Oppositely, in area 8 the mode is two points higher than the majority.
Comparing wind tunnel tests results with the usual type of pedestrian activity in respective areas it can be observed that in most areas pedestrian wind comfort is provided. Therefore, the results of wind comfort according to wind tunnel tests are at least at the level that allows for the usual type of pedestrian activity. Only area 2 does not fulfill its destination because pedestrian wind comfort according to wind tunnel test is provided for walking while this area is mainly used by people for sitting.
Taking into account the survey results the majority of people assessed wind comfort at least as moderately comfortable (rating: 3) in most of the areas (1, 4, 5, 6, 7, 8) which may confirm that they feel comfortably with respect to wind condition. However, for areas 1 and 6 the mode is much lower (two points lower) than majority rating which highlights poor wind conditions in these areas. Also survey results for area 3 are not consistent with wind tunnel tests results because people assessed wind comfort in this area as uncomfortable (rating: 2). On the other hand, the results of wind tunnel tests are reflected in low surveys ratings for area 2 so as in high survey results for area 8.
Summing up the comparison, results of wind tunnel tests and surveys are in quite good agreement. However, wind comfort assessment using comfort criteria was quite higher in some areas than according to field surveys which seems that the applied wind comfort criteria slightly overestimate pedestrian wind comfort. The comparison provides important information that threshold values proposed in NEN 8100 and in Lawson criteria may be suitable for the social profile of people and local weather conditions in the analyzed region. However, a modification is required to provide information about wind conditions experienced by the majority of people in this region.

4. CALCULATIONS OF THRESHOLD WIND SPEED

When assessing pedestrian wind comfort, adopting a threshold wind speed value V_{TRH} is a crucial step. As was shown in the previous sections, it seems reasonable to consider this value as a wind speed that causes discomfort to the general population. In this section, the results of the field measurements and surveys are compared to define the relationship between threshold wind speed and wind comfort rating, taking into account pedestrian activity or air temperature.
Two types of threshold wind speed (V_{TRH}) were calculated based on field measurements: mean and unsteady. The mean value of field wind speed ($\bar{V}_{field}$) was obtained as wind speed averaged for each of the 8 areas during the single measurement day. Unsteady field wind speed ($\hat{V}_{field}$) was calculated as the sum of the mean value of field wind speed ($\bar{V}_{field}$) and standard deviation of the measured wind speed for each of the 8 areas in the single measurement day. The unsteady wind speed was calculated because, as it was mentioned before, according to previous investigations people are more vulnerable to fluctuations in the wind speed [20].
Threshold wind speed (V_{TRH}) for different types of activities and ranges of air temperature was calculated according to the following procedure:

1. For each area (area=1:8) and each measurement day (measurement=1:10), mean and unsteady field wind speed ($\bar{V}_{field}$, $\hat{V}_{field}$) were calculated.
2. For each area (area=1:8) and each measurement day (measurement=1:10), the number of surveys with the same rating (rating=1:5) was determined. The sum of surveys with the same rating for each measurement day was calculated.
3. The matrix of products of field wind speed ($\bar{V}_{field}$, $\hat{V}_{field}$) and number of surveys with the same rating for each area and each measurement day was created. The averaged wind speed was calculated taking into account the sum

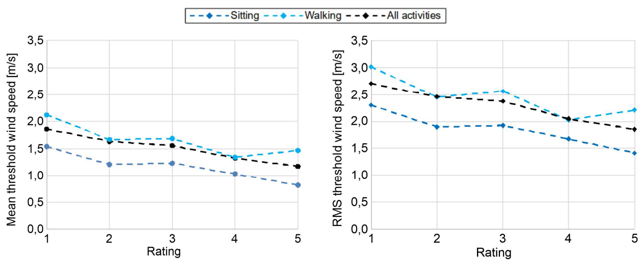

Fig.14. Threshold wind speed values (mean, unsteady) for different types of activities and concerning the self-assessed wind comfort rating

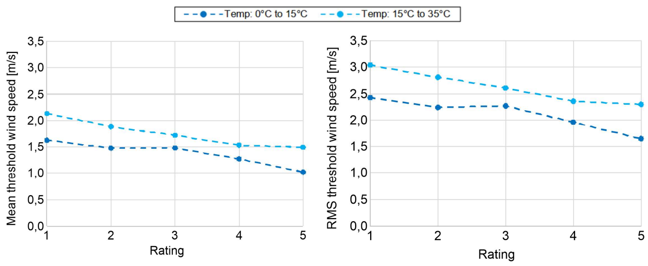

Fig.15. Threshold wind speeds (mean, unsteady) for different ranges of air temperature and concerning the self-assessed wind comfort rating

of surveys with the same rating for each measurement day and then taking into account the number of measurement days.

4. This averaged wind speed was adopted as the threshold wind speed (mean, unsteady) for a specific rating.

The above procedure was applied for all survey results, and dividing survey results into different types of activities and ranges of air temperature.

Figures 14 and 15 present the resulting threshold wind speeds (mean, unsteady) obtained for different ratings. Figure 14 shows the results for two different types of activities generally distinguished in the tested area: sitting and walking. Moreover, the results for all activities, without dividing between their type, are also presented. The results in Fig. 14 are provided for the whole range of air temperatures.

Generally, higher threshold wind speeds are observed for lower ratings (more uncomfortable wind conditions) and lower threshold wind speeds are observed for higher ratings (more comfortable wind conditions), which was expected as the higher wind speed, the worse the experience of wind conditions. The important observation from Fig. 14 is that the threshold wind speeds for sitting are lower than for walking for all the ratings. It also confirms that people have different expectations of wind conditions depending on the type of activity, which is already included in most of the wind comfort criteria.

According to the modified Beaufort scale [21] the 3rd and 4th degree of scale correspond to mild and moderate wind. This can result in hair movement and cause difficulty in reading a paper. This occurs when mean wind speed ranges between 2.4 m/s and 5.5 m/s. It corresponds to unsteady wind speed 1.6 m/s and 3.7 m/s if we take into account assumption proposed by [21] that unsteady winds cause similar effects as steady winds at 1.5 times lower speed. This description is in close agreement with the field measurements results for unsteady wind speed for sitting presented in fig. 14 which ranges between 1.5 m/s and 2.5 m/s.

Using the same modified Beaufort scale it appears the risk of losing balance when entering a wind zone and wind action is felt on the body at 5th scale degree representing refreshing wind. Mean wind speed range for 5th degree is between 5.6 m/s and 7.5 m/s which corresponds with unsteady wind speed in the range between 3.7 m/s and 6.4 m/s. The lower wind speed value is consistent with value of the unsteady wind speed for walking measured in field tests which ranges between 2 m/s and 3.1 m/s.

The results presented in Fig. 15 concern all types of activities for two different ranges of air temperature: between 0°C and 15°C, between 15°C and 35°C. The results presented in Fig. 15 show a correlation between air temperature and threshold wind speed, which increases with higher temperatures. The trend of increasing threshold wind speed with decreasing rating is also observed in each range of air temperatures.

It is worth highlighting that mean threshold wind speeds at which people assessed wind conditions as unfavorable (rating 1) are low (about 2 m/s) compared with threshold wind speeds defined in most wind comfort criteria. However, it may be the effect of turbulent character of wind in urban area. Even if the threshold wind speed was unsteady, the obtained threshold value still remains low (about 3 m/s). It should be considered if threshold wind speed is defined as the gust or unsteady value (as it is also proposed in some of the comfort criteria, e.g. in Lawson criteria [13]) to take into account the influence of unsteady winds on people's sensation of wind.

Threshold wind speeds presented in Figs. 14 and 15 were derived from all pedestrian survey data, including only cases where at least 5% of respondents in a given area rated wind comfort at a particular level on a single measurement day. The results allow to make general observations about the influence of wind speed on wind comfort sensation as actually experienced by pedestrians during different types of activity and at different temperatures. Nevertheless, to determine a threshold wind speed which could be used in defining pedestrian wind comfort criteria, further investigations are needed. However, the remarks presented in this paper should be taken into account – perhaps instead of one single value, a range of wind speeds for which wind comfort is provided should be defined, also putting more emphasis on the impact of the air temperature.

5. CONCLUSIONS

This paper presented the issue of pedestrian wind comfort as a problem affecting the entire population in the city centers with high-rise buildings. The field measurements conducted throughout the campaign give a novel insight into how people experience wind conditions. The results contribute to the knowledge of the influence of wind on people inhabiting city centers, tackling a current problem that is perhaps more serious than originally envisaged. In particular, the comparison of the survey results with the assessment of pedestrian wind comfort using different comfort criteria through the wind tunnel tests provides new and useful conclusions on the development of wind comfort criteria. Such comparison is necessary because, as it was mentioned in [22], the feedback from urban planners and people concerning pedestrian wind comfort is still not documented sufficiently.

The main conclusions which stem from this research are summarized below:

- The wind comfort criteria based on a fixed threshold wind speed or the range of threshold wind speeds with different limits of exceeding probability can be interpreted more easily by laymen, as they state an explicit limit value(s) of wind speed above which people experience discomfort. The final rating of wind comfort depends on how often these uncomfortable conditions occur.

- Wind tunnel tests are an essential practical tool in assessing pedestrian wind comfort. Nevertheless, they need to be conducted precisely, taking into account the areas where adverse wind conditions are expected to occur, hence the location of measurement points is crucial. Moreover, the wind comfort criteria which are the most suitable for a social profile of people living in a given area are required for proper evaluation as it was stated in [11].
- There is a significant influence of air temperature on how people experience wind comfort. This is a factor that should be taken into account when assessing pedestrian wind comfort. Due to this, the wind comfort criteria that distinguish at least two seasons (winter and summer) more accurately reflect the actual wind comfort in the regions where air temperature differs substantially during the year [15]. Moreover, there is still room to improve on defining the correlation between wind comfort criteria and air temperature through future investigations.
- The results of these measurements, as well as the observations of other authors, indicate that people are more vulnerable to unsteady winds which cause their discomfort at lower wind speeds than steady winds [20]. This is even more pronounced in the densely developed areas in the city centers, characterized by high turbulence, where both local wind speed and wind direction change frequently. Therefore, it should be considered when preparing comfort criteria for Poland if wind comfort criteria should take into account unsteady wind speed of lower value than assumed in the wind comfort criteria included in this paper.
- The results of the tests presented in this paper are promising and open a possibility to be further expanded in the future through subsequent campaigns to provide a better understanding of pedestrian wind comfort in city centers. Different areas and cities with high-rise buildings should be investigated to compare if people experience wind comfort in a similar way and what are the reasons for potential differences. However, the presented investigations are a satisfactory first step to initialize a larger campaign with the goal of providing uniform and quantitative pedestrian wind comfort criteria in Poland that would be strongly based on a scientific basis.

Summing up, the following aspects must be considered in any future investigation into the establishment of pedestrian wind comfort criteria for Poland:

- the division into different seasons of the year (summer, winter) is to be incorporated,
- a comprehensive analysis of wind flow characteristics (steady, unsteady, turbulence level) should be undertaken,
- the prevailing type of pedestrian activity should be taken into account,
- the probabilities of threshold velocity exceedance in accordance with NEN 8100 or Lawson criteria are to be considered for the establishment of comfort criteria.

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