BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 73(6), 2025, Article number: e154725
DOI: 10.24425/bpasts.2025.154725

SPECIAL SECTION

Pedestrian wind comfort in large cities

Agnieszka KOCOŃ[1,2]*, **Renata KŁAPUT**[1], **Aleksander PISTOL**[3], and **Agata SZELĄG**[1]

[1] Cracow University of Technology, Krakow, 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 the 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 3200. The analyzed area is then recreated in a model scale and tested at a wind tunnel facility. The results obtained 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 a low unsteady wind speed of around 3 m/s. The results of the research campaign provide a better understanding of pedestrian wind comfort in the cities and support improved planning and design practices in urban environments.

Keywords: 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 being too low (potentially causing stagnation of pollution [1]) or being 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 and social disadvantages. Moreover, adverse wind conditions cause many complaints from urban residents and workers, having an impact on their mood and overall quality of life 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 is likely to 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 analyses [8]; they also enable us to predict wind conditions in future urban development projects. Field studies are another method to assess pedestrian wind comfort [9], whose advantage is obtaining real wind conditions prevailing in the analyzed area; however, its limitation is that it can be applied only in the current state of urban development for a 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 that should be considered 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 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.

Despite this complexity, many researchers have 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 of particular regions. The research comparing wind comfort criteria based on a case study [11] clearly shows

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

Manuscript submitted 2025-02-12, revised 2025-05-19, initially accepted for publication 2025-05-20, published in November 2025.

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. 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. This problem was thoroughly examined through in-situ measurements and wind tunnel tests. Surveys concerning the individual feelings 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-reported by the local population, considering 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 scarce works that 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 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.

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, with a notable deterioration of wind comfort conditions signaled in this 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 (compare Fig. 1). All these factors combined suggest that problems with the windy environment in this area may gain even more importance in the future.

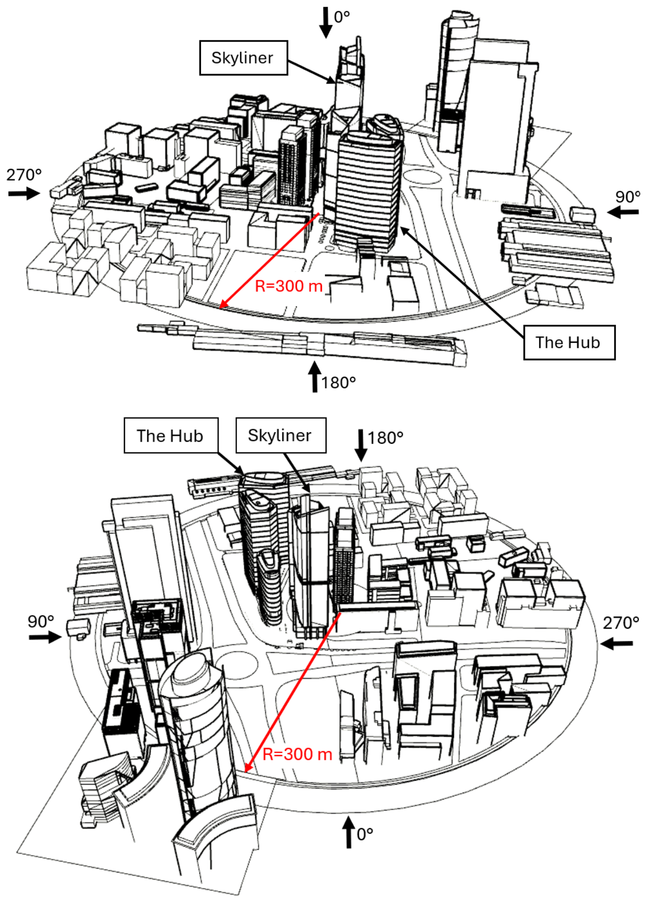

Fig. 1. 3D schematic view of the measurement location (dimensions in real scale)

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.

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 feelings 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.

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's wind comfort, while 2965 respondents answered

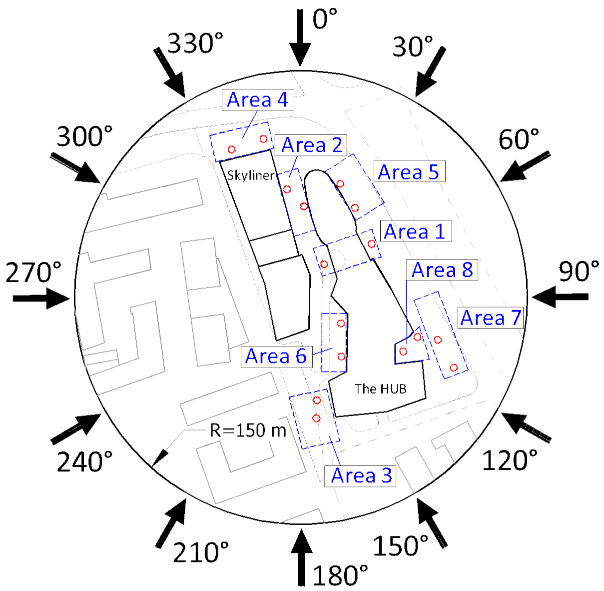

Fig. 2. Location of the areas (marked in blue) and measurement points (marked in red) where pedestrian wind comfort was analyzed with respect to wind directions (dimension in real scale)

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

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 ten days throughout different seasons (two days in February, three days in April, two days in May, three days in June), hence the analysis encompassed different weather conditions. The number of surveys for each area was either 25 or 50 per day; the total number of surveys was 3200, 400 for each area.

Concurrently with the surveys, the measurements of weather parameters took place in the eight areas marked in Fig. 2. The weather parameters were measured usually for 15 minutes in one

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?	A few times a week – every day
		A 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

area, and then the measurement location was changed to another area. The measurements were taken while collecting the surveys; however, not taken for the entire period of collecting the surveys in a 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 0.5 m/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 taken 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 at 16 points; each area included 2-measurement points. Simultaneously (Fig. 2), the 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.

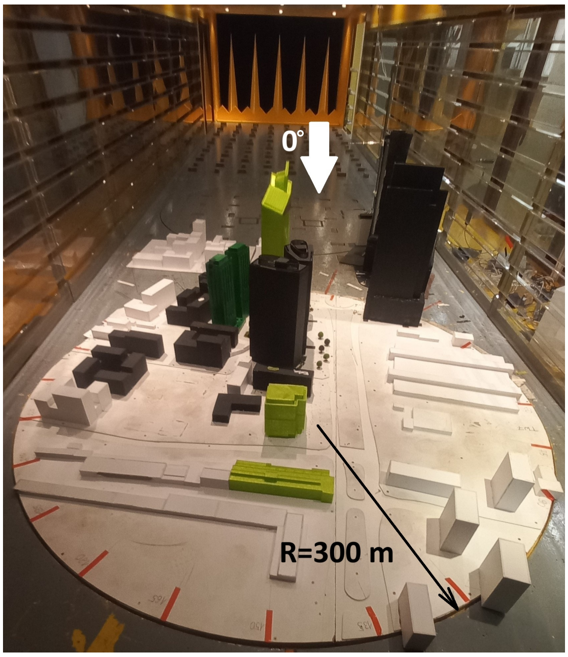

Fig. 3. Measuring position in the wind tunnel (dimension in real scale)

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 to the location of the subject area was simulated using the appropriate turbulence elements such as barriers, spires, and blocks. It enabled modeling the structure of the wind flow representing terrain category IV according to [18], which is characteristic of 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, the wind speed amplification coefficient with respect to the wind direction (θ_i) was calculated for each measurement point and wind direction

$$\gamma(\theta_i) = \bar{V}_P(\theta_i)/\bar{V}_{\text{ref}}(\theta_i), \tag{1}$$

where $\bar{V}_P(\theta_i)$ – mean wind speed at the pedestrian level at point P, $\bar{V}_{\text{ref}}(\theta_i)$ – mean wind speed at the reference height.

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

$$P_{\text{exc}}(\theta_i) = 100 \cdot P(\theta_i) \cdot \exp\left[-\left(V_{\text{TRH}}/(\eta(\theta_i)\cdot\gamma(\theta_i)\cdot\beta(\theta_i)\cdot c(\theta_i))\right)^{k(\theta_i)}\right], \tag{2}$$

where V_{TRH} – threshold wind speed, $P(\theta_i)$ – probability of wind direction θ_i (obtained from a wind rose for a specific region), $c(\theta_i)$ – scale and $k(\theta_i)$ – shape parameter of the Weibull distribution function, $\eta(\theta_i)$ – time averaging coefficient, $\gamma(\theta_i)$ – wind speed amplification coefficient, $\beta(\theta_i)$ – transition coefficient.

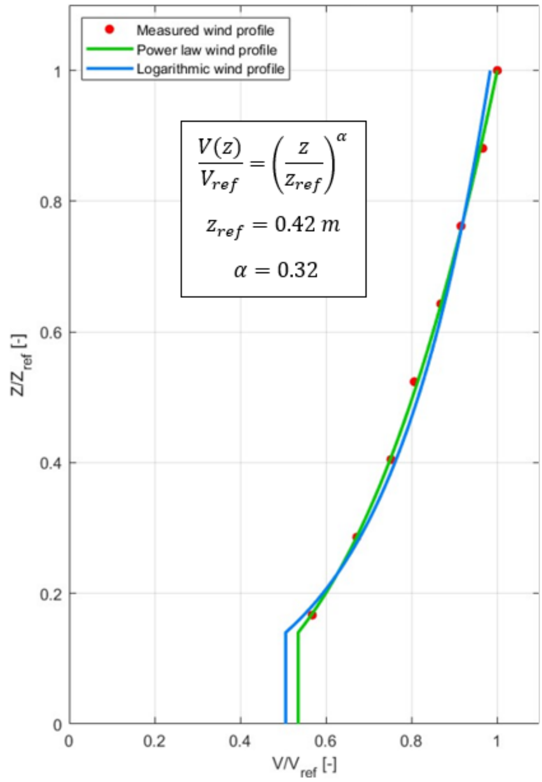

Fig. 4. Mean wind speed profile

Data from the meteorological station in Warsaw's Okęcie district, used in these calculations (frequency wind rose and Weibull distribution parameters based on 10-minute mean wind speeds), were obtained from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB, the main Polish body that gathers meteorological data and informs the public and organizations of atmospheric conditions). The distance between the 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 ($P_{\text{exc}}(\theta_i)$). 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: $V_{\text{TRH}} = 5$ 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.

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

Levels of wind speed (V_{TRH}) for different pedestrian activities are established for this threshold probability. Five types of

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%

pedestrian activity are adopted in the 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.

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

It should be noted that by default, the Lawson criteria consider gust velocities – either GEM (gust equivalent mean) or maximal moving average from a period of three 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, considering 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.

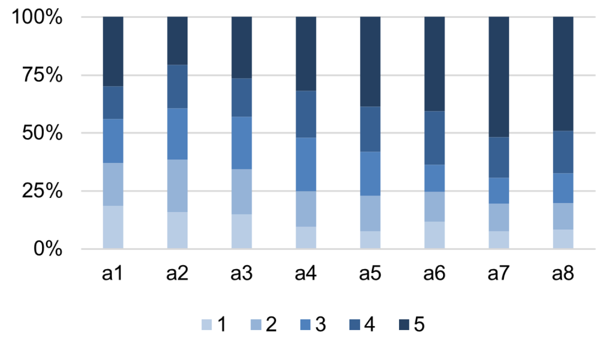

Fig. 5. The assessment of today wind comfort (TWC) according to field surveys

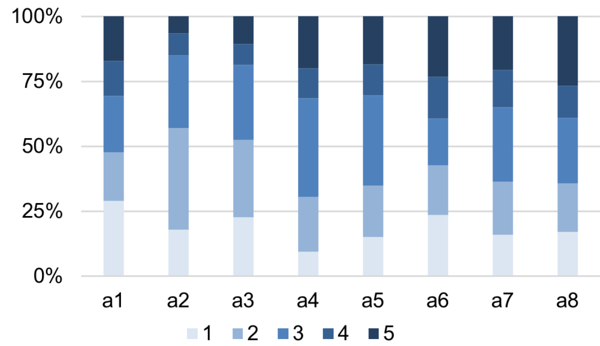

Fig. 6. The assessment of pedestrian wind comfort prevailing usually (UPWC) according to field surveys

Analysis of variance ANOVA was performed to examine data distribution. The significance value was calculated based on the entire range of data concerning usually prevailing wind comfort results (UPWC) for each area separately, considering five subgroups of different ranges of ages. For the areas in which the significance level indicated that differences between results in some subgroups may appear, post hoc tests were conducted. For six out of eight areas, no significant differences between subgroups were indicated. For the remaining two areas lower significance value may result from a smaller amount of data collected for one of the two groups, where the lower significance value was obtained.

Assessment of TWC shows that each area is rated differently. Considering the rating of most respondents, they assessed wind comfort in areas 1, 2, and 3 as at least 3 (moderately comfortable); in areas 4, 5, 6, and 8 as at least 4 (comfortable), and in area 7 as 5 (very comfortable).

The results from the UPWC assessment show that most. Respondents evaluated wind comfort in areas 2 and 3 as at least 2 (uncomfortable); in areas 1, 4, 5, 6, 7, and 8 as at least 3 (moderately comfortable). These results were significantly different from the results obtained for the TWC assessment. Unsurprisingly, it can be concluded that over a longer time, people tend to evaluate the wind comfort conditions as more "moderate," i.e., 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. The main observation, which was already indicated, is that the results of TWC are 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 the 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 the ten days of measurements, when different atmospheric conditions prevail, people could assess wind comfort in the entire range of ratings; hence, the bias in TWC is obvious. Nevertheless, for UPWC, such variability in responses proves that wind sensation is subjective. Consequently, to evaluate wind comfort for the population, it is necessary to implement an averaging process.

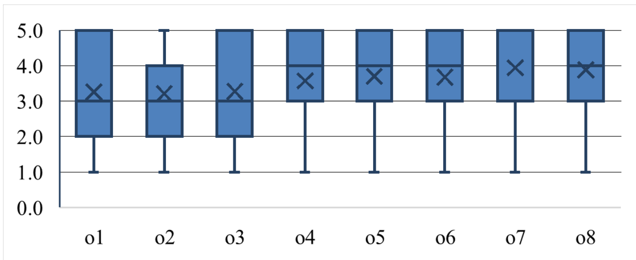

Fig. 7. Data distribution of the assessment of today wind comfort (TWC) (used symbols: cross – average, horizontal line – median, box plot – data between 25th and 75th percentile, whisker plot – data between 5th and 95th percentile)

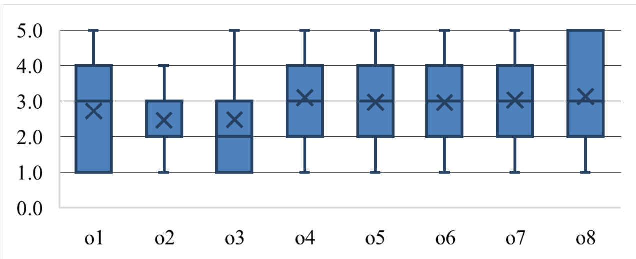

Fig. 8. Data distribution of the assessment of pedestrian wind comfort prevailing usually (UPWC) (used symbols: cross – average, horizontal line – median, box plot – data between 25th and 75th percentile, whisker plot – data between 5th and 95th percentile)

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 a different score than wind comfort which they usually experienced in this specific area. Therefore, it may be concluded that people can 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 the criteria, 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 ten days of measurements. The charts present the rating of most 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 – maximum and minimum – measured during the survey, with a trend line marked for the TWC rating. The second set shows the TWC rating with respect to mean and gust (maximum) wind speed.

The trend line for the TWC rating shows a general improvement in wind comfort over the course of measurement days (spread across three 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 a 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 today's worse 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 in 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 a higher TWC rating for the 2nd day 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 pointing 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

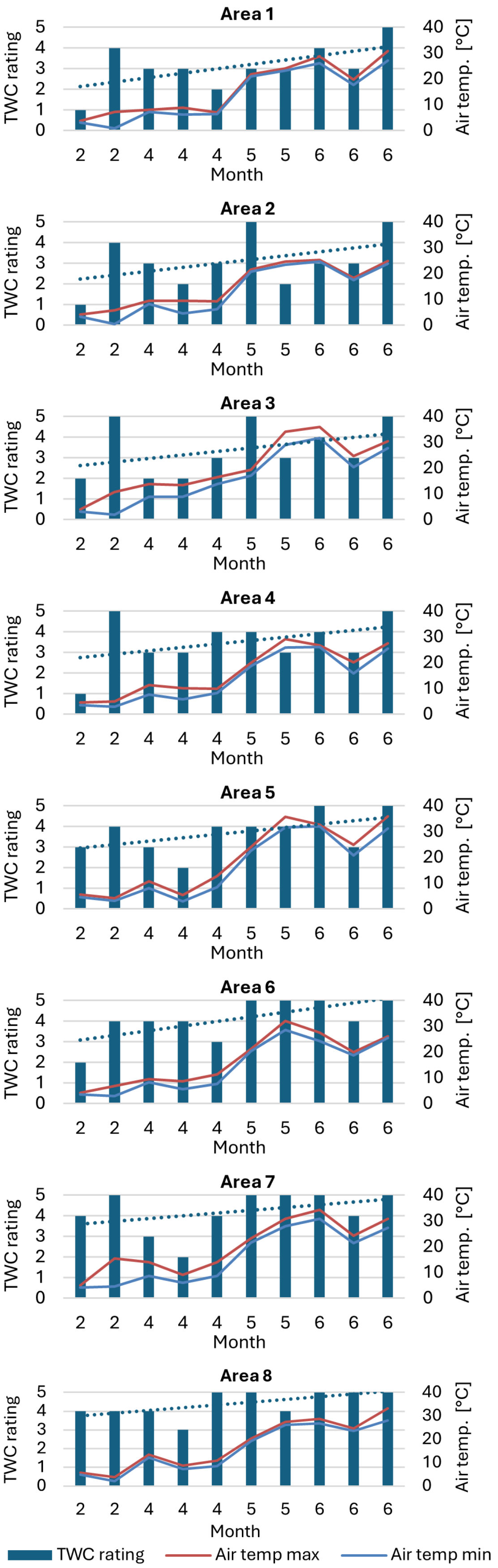

Fig. 9. Relationship between TWC rating and air temperature with respect to month (2 – February, 4 – April, 5 – May, 6 – June)

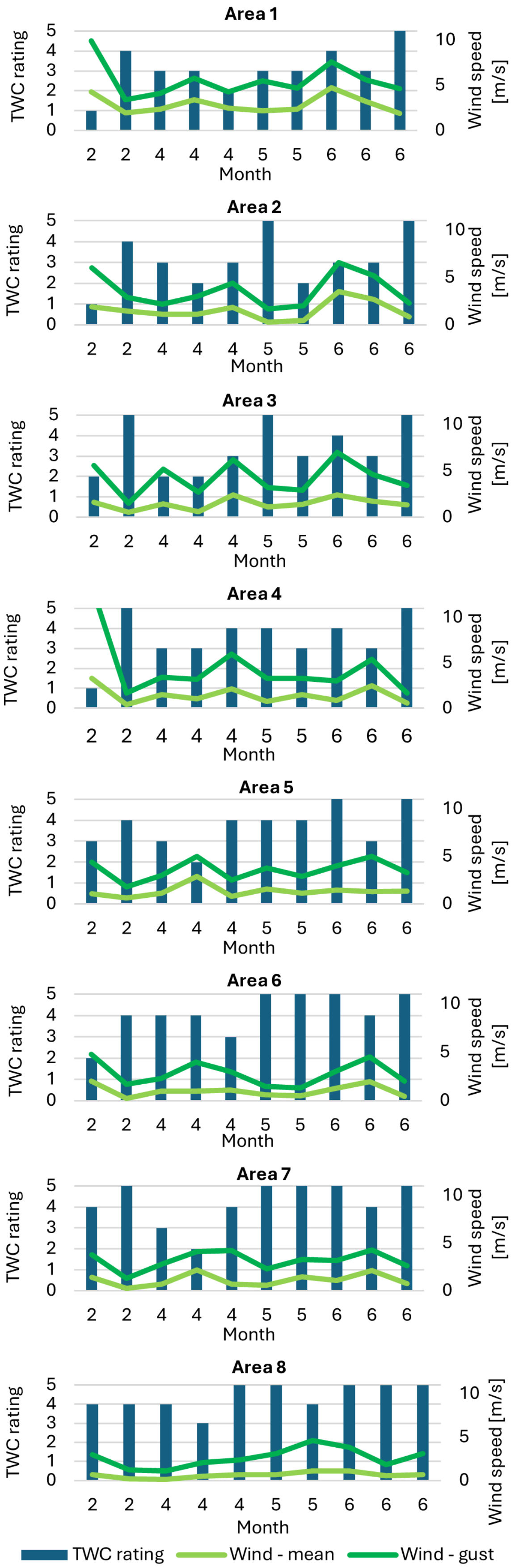

Fig. 10. Relationship between TWC rating and wind speed with respect to month (2 – February, 4 – April, 5 – May, 6 – June)

demands regarding 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., comparing measurements from the 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 the daily mean and gust wind speeds measured throughout the 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 decreased over the previous day. This trend is observed for the measurements conducted on the 1st day in May and the 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 to 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 reported on warm days (measurements on the 3rd day in May, 1st and 3rd day in June). People noticed that during the hot days, wind is desirable and sometimes complained that the wind speed was too weak. This remark was reported in the 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, the 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 us 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 a bar chart showing the percentage of answers that received a 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 to analyze whether the specific region fulfils its function considering results of field measurements and wind tunnel tests.

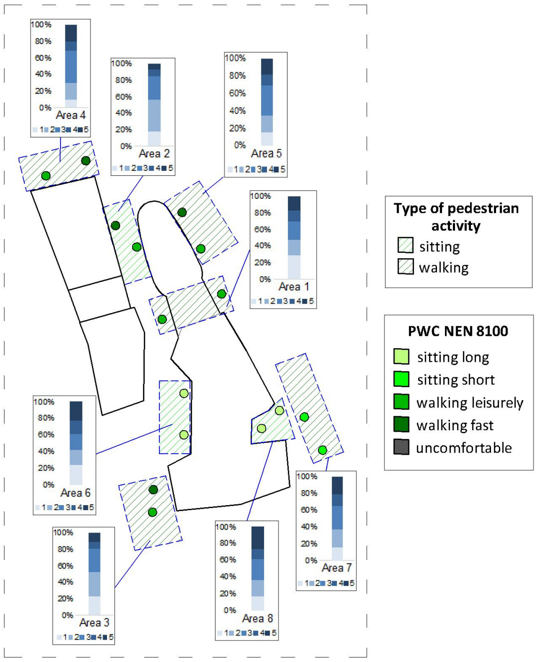

Fig. 11. Results of field surveys (bar chart) and wind tunnel tests (colored dots) using NEN 8100 criteria with usual types of pedestrian activities (hatched) in respective areas

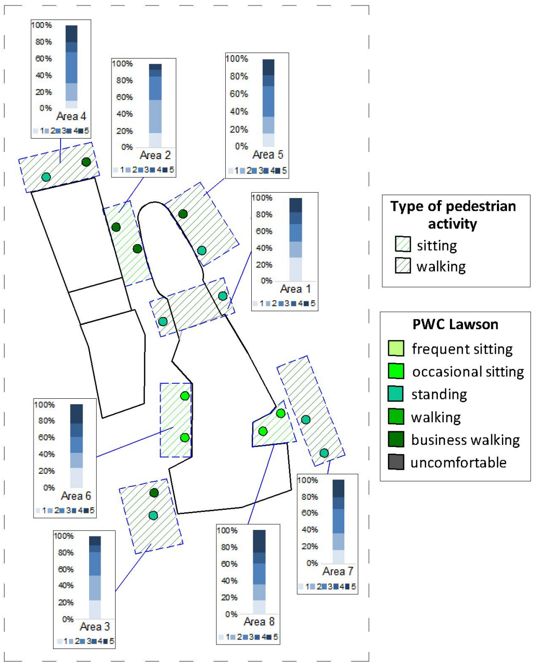

Fig. 12. Results of field surveys (bar chart) and wind tunnel tests (colored dots) using Lawson criteria with usual types of pedestrian activities (hatched) in respective areas

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 averaging 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 tend to walk through (defined in Figs. 11 and 12 as walking) should at least meet comfort criterion for fast walking while areas where people tend to sit or rest (defined in Figs. 11 and 12 as sitting) should at least meet comfort criterion on sitting short as illustrated in Fig. 13. Above the bar chart, two types of results from field surveys are compared: the rating which was most indicated by respondents (mode) and the rating which represents that most respondents rated wind comfort at that value or above (majority).

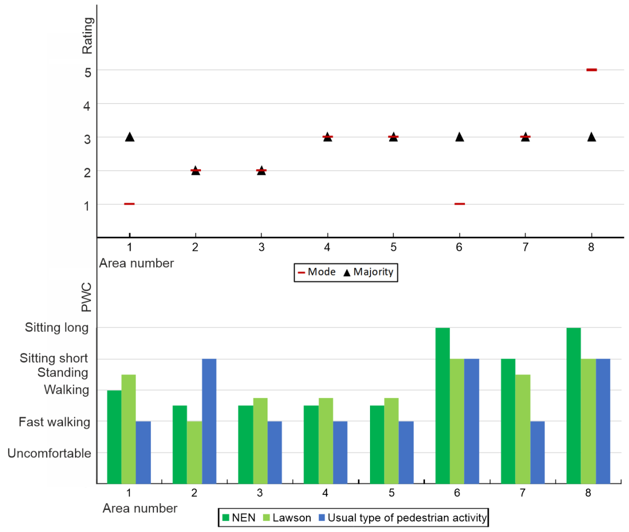

Fig. 13. Comparison of pedestrian wind comfort rating from field surveys (point chart) and wind tunnel tests (bar chart) using NEN 8100 comfort criteria (NEN) and Lawson criteria (Lawson)

The results show that the 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). Conversely, in area 8, the mode is two points higher than the majority.

Comparing wind tunnel test 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 purpose because pedestrian wind comfort, according to the wind tunnel test, is suitable for walking, while this area is 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 comfortable with respect to wind conditions. However, for areas 1 and 6, the mode is much lower (two points lower) than the majority rating, which highlights poor wind conditions in these areas. Also, survey results for area 3 are not consistent with wind tunnel test 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 survey ratings for area 2, as in high survey results for area 8.

Summing up the comparison, the 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 suggests that the applied wind comfort criteria slightly overestimate pedestrian wind comfort. The comparison provides essential information that the threshold values proposed in NEN 8100 and in the Lawson criteria may be suitable for the social profile of people and local weather conditions in the analyzed region. Nevertheless, a modification is required to provide information about wind conditions experienced by most people in this region.

4. CALCULATIONS OF THRESHOLD WIND SPEED

When assessing pedestrian wind comfort, a crucial step is adopting a threshold wind speed value (V_{TRH}). 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, considering 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 the field wind speed ($\bar{V}_{\mathrm{field}}$) was obtained as wind speed averaged for each of the eight areas during the single measurement day. Unsteady field wind speed ($\hat{V}_{\mathrm{field}}$) was calculated as the sum of the mean value of field wind speed ($\bar{V}_{\mathrm{field}}$) and the standard deviation of the measured wind speed for each of the eight areas on a single measurement day. The unsteady wind speed was calculated because, 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 ($\bar{V}_{\mathrm{field}}$, $\hat{V}_{\mathrm{field}}$) 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 ($\bar{V}_{\mathrm{field}}$, $\hat{V}_{\mathrm{field}}$) and the number of surveys with the same rating for each area and each measurement day was created. The average wind speed was calculated by considering the sum of surveys with the same rating for each measurement day and then considering the number of measurement days.
4. This average wind speed was adopted as the threshold wind speed (mean, unsteady) for a specific rating.

The above procedure was applied to all survey results and dividing the 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 distinguished in the tested area: sitting and walking. Moreover, the results for all activities, without dividing them into types, are also presented. The results in Fig. 14 are provided for the whole range of air temperatures.

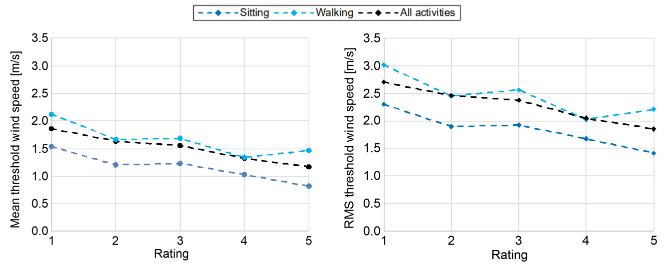

Fig. 14. Threshold wind speed values (mean, unsteady) for different types of activities and concerning the self-assessed wind comfort rating

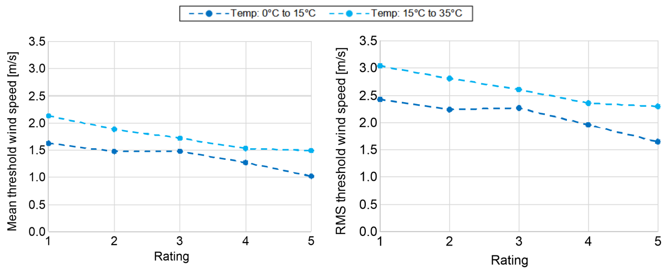

Fig. 15. Threshold wind speeds (mean, unsteady) for different ranges of air temperature and concerning the self-assessed wind comfort rating

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 the 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 degrees of scale correspond to mild and moderate wind. This can result in hair movement and cause difficulty in reading a paper. This occurs when the mean wind speed ranges between 2.4 m/s and 5.5 m/s. It corresponds to unsteady wind speeds of 1.6 m/s and 3.7 m/s if we consider the 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, ranging between 1.5 m/s and 2.5 m/s.

Using the same modified Beaufort scale, the risk of losing balance when entering a wind zone and the perception of wind on the body are observed at the 5th scale degree, representing refreshing wind. Mean wind speed range for the 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 the value of the unsteady wind speed for walking measured in field tests, ranging 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, and 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 both ranges of air temperatures.

It is worth highlighting that the mean threshold wind speeds at which people assessed wind conditions as unfavorable (rating 1) are low (about 2 m/s) as compared with threshold wind speeds defined in most wind comfort criteria. However, it may be the effect of the turbulent character of the wind in urban areas. Even if the threshold wind speed was unsteady, the obtained threshold value remains low (about 3 m/s). It should be considered if the threshold wind speed is defined as the gust or unsteady value (as is also proposed in some of the comfort criteria, e.g., in Lawson criteria [13]) to consider 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 each area rated wind comfort at a particular level on a single measurement day. The results allow us 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 that could be used in defining pedestrian wind comfort criteria, further investigations are needed. However, the remarks presented in this paper should be considered – rather than relying on one single value, it may be more appropriate to define a range of wind speeds for which wind comfort is provided, 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 offer 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 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 a 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 stemming 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 laypeople, 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, considering the areas where adverse wind conditions are expected to occur; hence, the location of measurement points is crucial. Moreover, the wind comfort criteria that are the most suitable for a social profile of people living in each area are required for proper evaluation, as stated in [11].
- There is a noteworthy influence of air temperature on how people experience wind comfort. This is a factor that should be considered when assessing pedestrian wind comfort. Due to this fact, 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 whether wind comfort criteria should consider the unsteady wind speed of a 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 whether people experience wind comfort in an analogous way and what the reasons for potential differences are. However, the presented investigations are a satisfactory first step to initialize a larger campaign to provide 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 considered.
- The probabilities of threshold velocity exceedance in accordance with NEN 8100 or Lawson criteria are to be considered for the establishment of comfort criteria.

ACKNOWLEDGEMENTS

This research was funded in whole by the National Science Centre, Poland under Grant No. 2023/07/X/ST8/00571. For Open Access, the authors have applied a CC-BY public copyright license to any Author Accepted Manuscript (AAM) version arising from this submission.

REFERENCES

[1] M. Shirzadi and Y. Tominaga, "Computational fluid dynamics analysis of pollutant dispersion around a high-rise building: Impact of surrounding buildings," *Build. Environ.*, vol. 245, p. 110895, 2023, doi: 10.1016/j.buildenv.2023.110895.

[2] H. Mittal, A. Sharma, and A. Gairola, "A review on the study of urban wind at the pedestrian level around buildings," *J. Build. Eng.*, vol. 18, pp. 54–163, 2018, doi: 10.1016/j.jobe.2018.03.006.

[3] X. Shia, Y. Zhud, J. Duanc, R. Shaoc, and J. Wang, "Assessment of pedestrian wind environment in urban planning design," *Landsc. Urban Plan.*, vol. 140, pp. 17–28, 2015, doi: 10.1016/j.landurbplan.2015.03.013.

[4] E. Ng, C. Yuan, L. Chen, C. Ren, and J.C.H. Fung, "Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong," *Landsc. Urban Plan.*, vol. 101, pp. 59–74, 2011, doi: 10.1016/j.landurbplan.2011.01.004.

[5] L. Chen and C.M. Mak, "Integrated impacts of building height and upstream building on pedestrian comfort around ideal lift-up buildings in a weak wind environment," *Build. Environ.*, vol. 200, p. 107963, 2021, doi: 10.1016/j.buildenv.2021.107963.

[6] L. Chen and C. M. Mak, "Numerical evaluation of pedestrian-level wind comfort around "lift-up" buildings with various unconventional configurations," *Build. Environ.*, vol. 188, p. 107429, 2021, doi: 10.1016/j.buildenv.2020.107429.

[7] A. Flaga, A. Kocoń, R. Kłaput, and G. Bosak, "The environmental effects of aerodynamic interference between two closely positioned irregular high buildings," *J. Wind Eng. Ind. Aerodyn.*, vol. 180, pp. 276–287, 2018, doi: 10.1016/j.jweia.2018.07.024.

[8] J. Jacob and P. Sagaut, "Wind comfort assessment by means of large eddy simulation with lattice Boltzmann method in full scale city area," *Build. Environ.*, vol. 139, pp. 110–124, 2018, doi: 10.1016/j.buildenv.2018.05.015.

[9] J. Zou, Y. Yu, J. Liu, J. Niu, K. Chauhan, and C. Lei, "Field measurement of the urban pedestrian level wind turbulence," *Build. Environ.*, vol. 194, 107713, 2021, doi: 10.1016/j.buildenv.2021.107713.

[10] H. Koss, "On differences and similarities of applied wind comfort criteria," *J. Wind Eng. Ind. Aerodyn.*, vol. 94, pp. 781–797, 2006, doi: 10.1016/j.jweia.2006.06.005.

[11] W.D. Janssen, B. Blocken and T. van Hooff, "Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on whole-flow field data for a complex case study," *Build. Environ.*, vol. 59, pp. 547–562, 2013, doi: 10.1016/j.buildenv.2012.10.012.

[12] N. Isyumov and A.G. Davenport. "The ground level wind environment in built-up areas," in *Proceedings of fourth international conference on wind effects on buildings and structures*, Heathrow, UK: Cambridge University Press, pp. 403–422, 1975.

[13] T. Lawson. *Wind Effects on Buildings*, London: Applied Science Publishers LTD, 1980.

[14] W.H. Melbourne, "Criteria for environmental wind conditions," *J. Ind. Aerodyn.*, vol. 3, pp. 241–249, 1978, doi: 10.1016/0167-6105(78)90013-2.

[15] NEN 8100, "Wind comfort and wind danger in the built environment," Dutch standard, 2006. (in Dutch)

[16] A. Sanz-Andres and A. Cuerva, "Pedestrian wind comfort. Feasibility study of criteria homogenization," UWEBA, Brussels, B3.1-B3.10, 2004, doi: 10.1016/j.jweia.2006.06.004.

[17] A. Flaga, A. Pistol, P. Krajewski, and Ł. Flaga, "Aerodynamic and aeroelastic wind tunnel model tests of overhead power lines in triangular configuration under different icing conditions," *Cold Reg. Sci. Technol.*, vol. 170, p. 102919, 2020, doi: 10.1016/j.coldregions.2019.102919.

[18] PN-EN 1991-1-4 "Actions on structures. General actions. Wind actions," 2008.

[19] J. Wieringa and P.J. Rijkoort. *Windklimaat van Nederland*. Staatsuitgeverij Den Haag, 1983. (in Dutch)

[20] J.C.R. Hunt, E.C. Poulton, and J.C. Mumford, "The effects of wind on people; New criteria based on wind tunnel experiments," *Build. Environ.*, vol. 11, no. 1, pp. 15–28, 1976, doi: 10.1016/0360-1323(76)90015-9.

[21] B. Blocken and J. Carmeliet, "Pedestrian Wind Environment Around Buildings: Literature Review and Practical Examples," *J. Therm. Envelope Build. Sci.*, vol. 28, no. 2, pp. 107–159, 2004, doi: 10.1177/1097196304044396.

[22] E. Willemsen and J.A. Wisse, "Design for wind comfort in The Netherlands: Procedures, criteria and open research issues," *J. Wind Eng. Ind. Aerodyn.*, vol. 95, pp. 1541–1550, 2007, doi: 10.1016/j.jweia.2007.02.006.