



An analysis of wind conditions at pedestrian level in the selected types of multi-family housing developments

Marta Poćwierz¹ · Katarzyna Zielonko-Jung²

Received: 22 September 2019 / Accepted: 18 August 2020 / Published online: 26 August 2020
© The Author(s) 2020

Abstract

The following article addresses the issue of wind conditions around urban building development at pedestrian level. Factors that depend on those issues include wind comfort and air quality within urbanized spaces. The conditions specific of cities located in a temperate climate zone have been taken into account. The article is intended to identify aerodynamic phenomena characteristic of the three basic types of multi-family building development (section, linear, quarter). For each type of buildings, three different variants were considered on the basis of land use efficiency (low, medium, high) each type of buildings is characterised with. The models illustrate the patterns observed within European urban planning thought and have been developed in accordance with contemporary architectural and urban conditions, as well as with legal requirements and good practices in force in Poland. Experimental research in the wind tunnel has been conducted by means of two complementary field methods (visualization and erosion). The application of these two methods made it possible to obtain data on airflow direction layouts and on changes in airflow velocity. Subsequently, the results obtained in the study have been compared. Thus, more and less favourable geometrical layouts in respect to aerodynamic phenomena have been indicated.

Keywords Environmental wind engineering · Airflow around buildings · Sustainable city · Multi-family housing · Urban planning

1 Introduction

Development of modern big cities gives rise to a number of issues, one of which seems especially serious, namely the need to improve the quality of big city mesoclimate conditions. Mesoclimate conditions are related to wind phenomena, which play a vital role in

✉ Katarzyna Zielonko-Jung
katarzyna.zielonko-jung@pg.edu.pl
Marta Poćwierz
mpocwie@meil.pw.edu.pl

¹ Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Nowowiejska 24 Street, 00-665 Warsaw, Poland

² Faculty of Architecture, Department of Environmental Design, Gdańsk University of Technology, G. Narutowicza 11/12 Street, 80-233 Gdańsk, Poland

ensuring proper ventilation of urban spaces, allow for temperature regulation and pollution removal. In temperate climate zone, a necessity arises to limit the occurrence of phenomena that either excessively intensify airflow velocity (for the sake of pedestrian comfort and for protection of buildings against excessive cooling) or that limit air circulation. The latter goal is crucial in order to avoid the problem of urban heat island, as well as to minimise the problem of smog, both of which are troublesome for big cities.

Research on airflow around buildings has been intensively developing since the mid-twentieth century [3, 4, 19]. As to a particular research that accounted for a breakthrough in the application of airflow research, J. Gandemer's experimental research from the 1970s should be mentioned. The research made it possible to distinguish twelve types of aerodynamic effects that occur around isolated buildings and around simple layouts of such buildings [14]. In the course of later studies, these phenomena were recognized more accurately by other authors [19]. Studies on street canyons conducted in the 1990s were especially important for urban planning. For example R. Walker, L. Shao and M. Wolliscroft conducted one of the first studies of natural ventilation via courtyards based on computational fluid dynamics [34]. These studies offered a better understanding of the relationship between airflow in urban spaces and the geometric form of complexes of buildings. Baik and Kim explored air circulation and the emergence of multiple vortices focusing on skimming flow relations in narrow courtyards [1]. The dependence of air circulation on the W/H parameter was observed and approximated figures for this correlation were provided, wherein the W/H parameter was expressed in terms of the distance between buildings (W) and their height (H). This knowledge has been further developed by many other authors and used as the basis for principles and recommendations for pro-ecological design consistent with the idea of sustainable development [11].

Research possibilities concerning aerodynamic phenomena around buildings have expanded considerably over the last 20 years, along with the development of numerical simulation methods. The principles for the application of these methods, as well as principles applied in order to combine the methods with experiments have been widely described in source literature [2, 15]. Most commonly, objects with simple geometrical layouts: free standing [20, 21, 23, 29] or regular layout of solids [3, 27] provide the research topic. Publications concerning more complex geometrical layouts that take the surroundings of a building into account are still relatively rare [5, 19, 30, 31, 35]. Such publications are dominated by case studies and concern specific types of building developments. Attempts to discuss model solutions that reflect the complex conditions commonly experienced in the process of urban development design are less numerous [18, 28, 31]. However, such publications seem particularly valid from the point of view of urban planning. Perhaps the lack of sufficient amount of publications on the topic is one of the reasons behind an infrequent application of the wind engineering theory in the practice of urban and architectural design.

The aforementioned previous studies clearly indicate that the airflow around buildings is closely related to the shape of a particular building development—the sizes and forms of individual buildings and their positioning in relation to one another. Several factors play a vital role for ventilation. They include: geometric proportions of streets [1, 8, 11, 34, 36], variations in building height [9, 26], building intensity expressed in Floor Aspect Ratio and Building Coverage Ratio [25, 29]. Moreover, geometric features, though not sufficiently tested yet, may exert an impact on the efficiency of urban ventilation [19]. These features include: porosity (the amount of empty spaces of an urban layout in which airflow can occur), orientation of the network of streets (related to the influence of building and street orientation on airflows), share of sheltered spaces (enclosures as a courtyards or



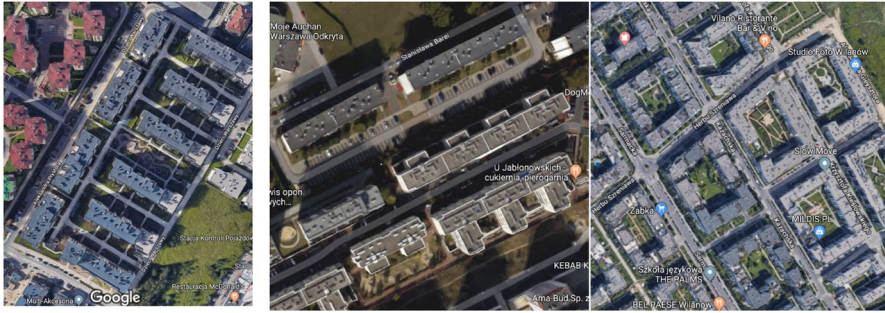


Fig. 1 Types of housing building developments from the left: section, linear and quarter, based on the example of building complexes erected in the recent years in Warsaw; source: Google maps

narrow, closed streets) [19]. Therefore, designing the shape of a new building is related to a modification of the aerodynamic phenomena in its surroundings. The conscious use of this dependence in urban and architectural design can positively affect the quality of the microclimate in spaces between buildings (in squares, streets, courtyards, parks, gardens, etc.), as well as it may indirectly influence the overall mesoclimate situation of the city.

The following article is intended to analyse aerodynamic phenomena that occur at pedestrian level around the three most common types of multi-family housing developments. Differences between individual variants were observed, whereas wind conditions that constitute pedestrian comfort within spaces between buildings and that account for the possibility of airing spaces between the buildings were compared. The models adopted for the present research exemplify the types of buildings most commonly seen in urbanized areas in a temperate climate zone. The authors' objective was to create such model objects that would be close to real issues observable in architectural and urban design, especially in case of Polish conditions (although the models can probably be applied to urbanized spaces of many other countries).

1.1 The subject of the research

Three types of multi-family building developments have been selected as the subject of the present research:

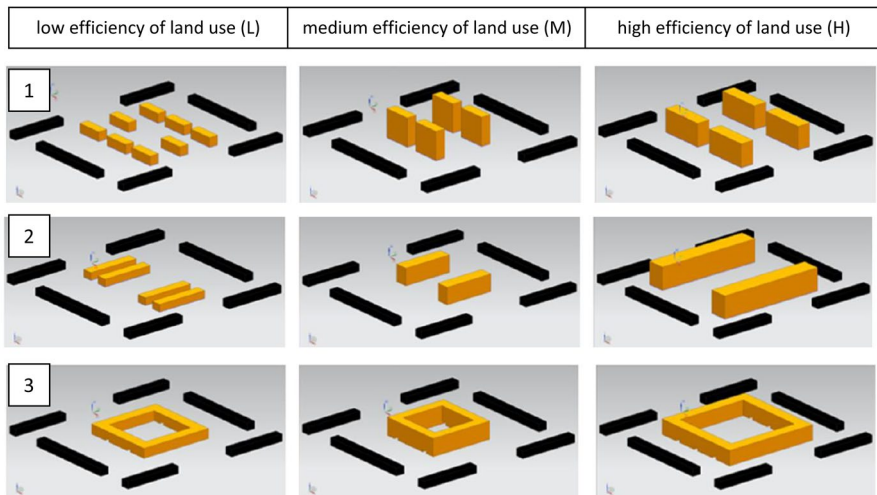
- Section developments - free-standing buildings with rectangular, but not overly elongated building plans,
- Linear developments - buildings with a considerably elongated rectangular plan,
- Quarter developments - a set of buildings that enclose a rectangular inner courtyard.

The aforementioned types of multi-family building developments are characteristic of the European architectural thought fostered since the beginning of the 20th century and continued to the present day. Such building developments can be found in the urban tissue of many Polish cities (Fig. 1) [16, 24].

Palladio, an architect, established theoretical geometric models that correspond to the above types of building developments [24]. The models illustrate land development of a square plot, covering an area of 2 hectares, on which an adequate amount of recreational and green spaces has been planned with reference to inhabitant numbers, as well as a proper

Table 1 Characteristics of types of land use efficiency source: Pallado [24]

	Land use efficiency (LUE)		
	Low	Medium	High
Land use [numbers of flats/plot area]	50–100 Flats/1 ha	100–200 Flats/1 ha	200–300 Flats/1 ha
Population density [number of inhabitants/plot areas]	150–300 Residents/1 ha	300–600 Residents/1 ha	600–900 Residents/1 ha
Development intensity [total area of storeys above the ground/ plot area]	0.50–1.00	1.00–2.00	2.00–3.00

**Fig. 2** Models of building developments selected for research: author's study based on Pallado (2014) [24]

amount of spaces for communication and parking purposes has been intended. Legal conditions in force in Poland have been taken into account (requirements for room insulation and lighting with daylight, for dimensions and position of roads, walkways, parking lots, etc.) and good design practices have been applied. Each model has been developed in three variants - for low, medium and high degree of land use efficiency (LUE). The land use efficiency has been defined by the three parameters enumerated below (the range of values has been provided in Table 1):

- Area use expressed in the number of flats per hectare of plot area,
- Population density expressed in the number of residents per hectare of plot area,
- Building development intensity expressed as the ratio of the total area of building developments (all above-ground storeys) to the area of the plot on which the development is situated.

The buildings in the models developed by Pallado (and applied in this research) are of the following heights (Fig. 2):

- Section building development - 12 m (4 storeys) for low LUE, 33 m (11 storeys) for medium LUE, 27 m (9 storeys) for high LUE,
- Linear building development - 9 m (3 storeys) for low LUE, 24 m (8 storeys) for medium LUE, 27 m (9 storeys) for high LUE,
- Quarter building development - 12 m (4 storeys) for low LUE, 21 m (7 storeys) for medium LUE, 18 m (6 storeys) for high LUE; in this case gateways were introduced on two opposite sides of the block (4 for low and medium LUE and 6 for high LUE).

Additionally, the research presented in the article takes into account the surrounding building development so as to recreate the urban context of exemplary layouts of building developments. In order to recreate the surrounding building development, elongated buildings of 9 m (3 storeys) in height have been chosen to form four streets adjacent to a square plot. A uniform environment has been assumed for all of the layouts of building developments tested.

2 Research methods

2.1 Research techniques

The research was conducted in an aerodynamic tunnel whose measuring space equals 1 m × 1 m. In order to depict properly the ground floor level, a ready-made set of obstacles has been introduced. The obstacles had been specifically designed in accordance with wind standards applied in the studies described in [6, 10, 12, 15, 17] and elsewhere. In this way, the desired profile of velocity, intensity and kinetic energy of turbulence were obtained. The building models adopted for research were created in 1:400 scale.

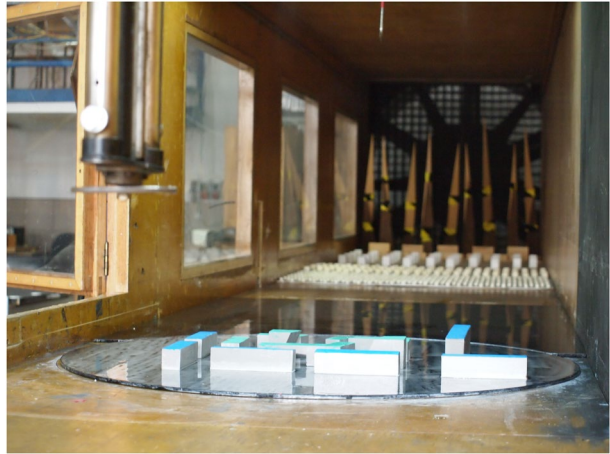
Two field techniques, namely visualization method and erosion method, have been applied to observe the aerodynamic phenomena that arise in the discussed urban layouts and to determine changes in wind velocity in immediate vicinity of the buildings. The two techniques complement each other. The first one determines the flow direction, the second one determines the changes in flow velocity. The advantage of the two methods may be seen in their simplicity and in relatively low performance costs. The results yielded by the two methods, though of qualitative nature, do accurately reflect the flow image and allow for a meticulous analysis [3, 6]. The areas where airflow accelerates, as well as areas of poor ventilation are clearly visible in the results. Moreover, it is possible to estimate the value of alteration in velocity in specific areas.

Of all visualization techniques available, the oil visualisation technique was chosen. In order to conduct research described in the article, a glass base, in black, to which the models were attached has been used. The glass base was painted with a mixture of oil and titanium dioxide, which served as a white marker (Fig. 3).

As a result of simulation in the wind tunnel, an image of the averaged moving air directions, as well as of a layout of vortex structures in the flow have been obtained. During the experiment, photos were taken at a frequency of four photos per minute. The analysis of the sequence of all the photos taken in a given trial allowed for a full understanding of the phenomena that occur in the flow and for a correct interpretation of such phenomena. The interpretation of the obtained phenomena was marked with graphical symbols in the last picture in each sequence (Figs. 6 and 8).



Fig. 3 Models of building development on the black glass base prepared for the research in the wind tunnel. In the background, elements used to model the boundary layer may be seen



The visualization technique was further supplemented with the erosion technique—namely, with sand erosion. The application of this method makes it possible to determine changes in airflow velocity values once an obstacle has been introduced (in the described studies such an obstacle is posed by layouts of buildings). A detailed description of the abovementioned technique can be found in [3, 6].

The experiment in which the erosion technique is applied consists of two stages. In the first stage, the reference speed should be determined. In this case, the plate with no models on it is evenly sprinkled with sand, while airflow velocity at which the layer of applied sand is almost completely blown off the plate is measured in the tunnel. Then, a plate with models of buildings attached to it and with sand spread evenly on the empty areas between the buildings is placed in the tunnel. Once the tunnel is launched, airflow velocity in it is gradually increased. After each alteration of speed, the airflow stabilizes, then a photo of the examined area is taken. In accordance with the principles behind the use of this technique, twelve pictures were applied and processed for each variant (for subsequent airflow velocities (Fig. 4). As a result, coloured maps that display distribution of wind amplification coefficient marked as α have been obtained (Fig. 5).

The relation

$$\alpha_n = \frac{U_{GB}}{U_{G,n}}$$

defines this coefficient, where U_{GB} denotes the ground-level wind speed that is influenced by the building and for which sand erosion occurs, and $U_{G,n}$ denotes the ground-level wind speed that is not influenced by the building. (Ground-level wind speed corresponds to the speed measured at the pedestrian level, i.e. at a height of about 1.75 m).

In the wind tunnel, all dimensions are rendered in a scale. For a tunnel that measures 1 m x 1 m, a height of 1.75 m corresponds to a height of 4.4 mm. It is difficult to measure the velocity accurately at this height, it is much easier to measure tunnel operating speed. It can be shown that to determine wind amplification coefficient it is enough to measure the speed anywhere in the tunnel.

Let U_w stand for the wind velocity measured at a certain height from the base of the tunnel (in our case this height was 0, 6 m). The velocity is gradually increased until the process of erosion begins and almost all the sand is blown off the plate. The value of U_{WB}



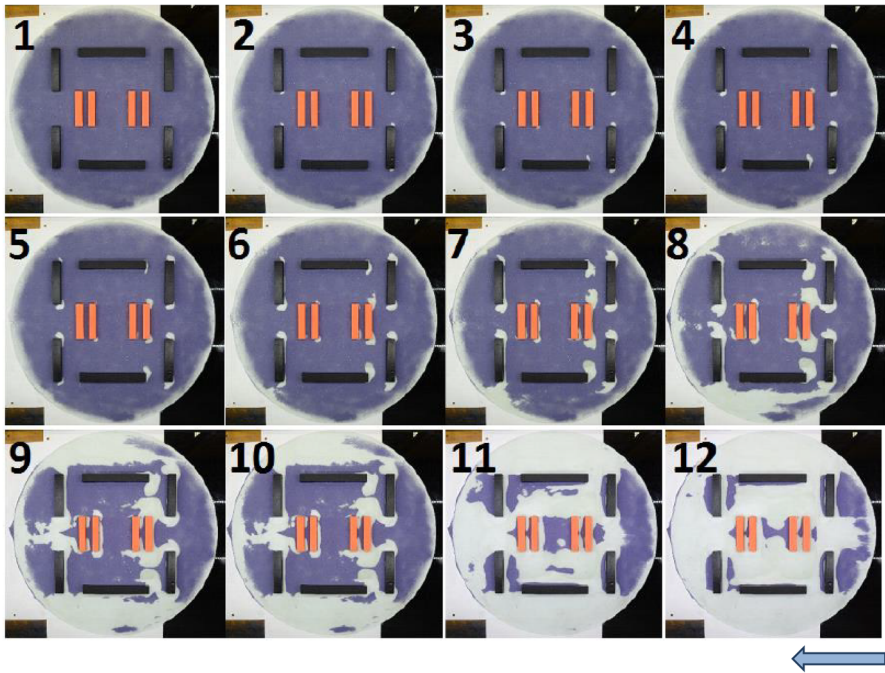


Fig. 4 Photographs taken during the research on the selected model building development with the use of sand erosion technique ordered according to the assumed flow velocities

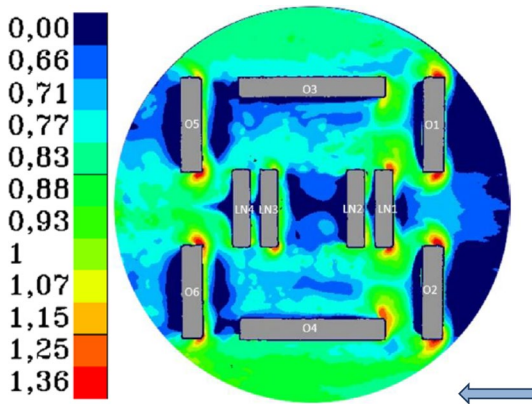


Fig. 5 An example of the final coloured map presenting the distribution of wind amplification coefficient— α , created on the basis of sand erosion for a selected model of building development; $\alpha \in (1.36–1.25)$ —zones of the strongest ventilation. Even at low wind velocity they are troublesome for pedestrians; $\alpha \in (1.07–1.15)$ —zones of lower intensity of ventilation, at average wind force, they create comfortable conditions for residents, whereas at very strong winds they are no longer as troublesome as red zones; $\alpha \in (0.83–1)$ —zones of good ventilation, both at low and high wind velocity; $\alpha \in (0.71–0.77)$ —zones of reduced airflow, which at regular wind conditions are characterized by low ventilation, relatively good at strong winds; $\alpha \in (0.66–0.00)$ zones of poor recirculation and a stagnation zone

is then proportional to the velocity at the ground-level, U_{GB} , at which the wind actually affects the sand. In the following stage of the research, buildings are attached to the cleaned plate and a layer of sand is applied once again. The flow velocity is increased gradually to the values of $U_{W,1}$, $U_{W,2}$, $U_{W,3}$, ... Before each modification to wind velocity in the tunnel, some amount of time is devoted to determine the shape of the area of the blown-off sand. These velocities correspond to velocities observable at ground-level $U_{G,1}$, $U_{G,2}$, $U_{G,3}$... An acceleration of flow near buildings may occur. In areas where the airflow velocity exceeds the U_{GB} value, sand is blown off. It should be noted that using dependencies

$$\frac{U_{W,1}}{U_{G,1}} = \frac{U_{W,2}}{U_{G,2}} = \dots = \frac{U_{WB}}{U_{GB}}$$

The wind amplification coefficient may also be written in the form of:

$$\alpha_n = \frac{U_{WB}}{U_{W,n}}$$

It should be noted that in the area where $\alpha > 1$, airflow accelerates, e.g., due to the presence of buildings. Conversely, for $\alpha < 1$ airflow slows down.

When the average or maximum wind velocity (V) in the city is identified at the pedestrian level, an approximate velocity in the presented built-up areas can be determined as $w = \alpha v$, based on the wind amplification coefficient.

Wind velocity in the climatic conditions in Poland fluctuates on an annual scale from 1.16 to 12.09 m/s, the average velocity equals about 3.5 m/s, while in case of a city, such as Warsaw, it reaches about 4 m/s [13]. Taking into account the wind comfort conditions presented in numerous publications [7, 8, 17, 22, 32, 33], the colour layout may be interpreted as described in the Fig. 5.

2.2 Method of research grouping and result comparison

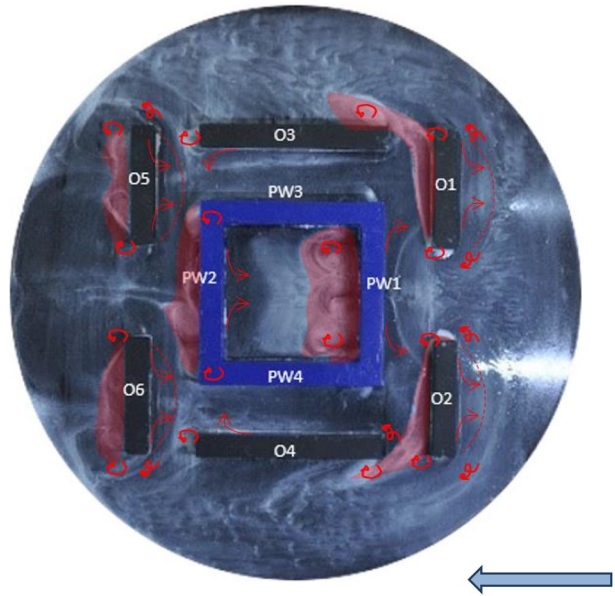
Each of the nine building development variants has been tested with the application of two techniques described above. Additionally, for each of them, three wind directions—paralleled, perpendicular and oblique (at 45° angle) were taken into account. Due to the almost complete symmetry of the building development layouts, it may be concluded that the results for winds of the same directions, but opposite turns would provide a symmetrical reflection.

Altogether, twenty-seven tests have been performed with the application of both techniques, the results have been compared using the following steps:

- a. The results for one type of building development have been analysed (starting with the section building development) for low, medium and high land use efficiency, in case of one (paralleled) wind direction. The results have then been compared;
- b. Analogous analyses and comparisons have been conducted, as described above, for the remaining wind directions (perpendicular and oblique ones);
- c. The results have been compared and a collective comparison has been made of the variants for one building development type (starting with the section development—three variants of land use efficiency and three wind directions);
- d. analogous actions have been performed (as in points a, b and c) with respect to the results obtained for other types of building developments (linear and quarter ones);



Fig. 6 A photograph presents the result of the oil visualization, together with a graphical interpretation of wind phenomena for the building with a high land use efficiency; the arrows indicate the direction of airflow and airflow turbulences, whereas a dashed line has been used to mark the boundary of vortex area. The stagnation zone is hatched



- e. The synthesized results for three types of building developments have been juxtaposed and compared in three variants of land use efficiency.

3 Results

Owing to a large number of partial results obtained in the study, an exemplary interpretation of the results for one type of building development, namely the quarter building development with a high land use efficiency in case of paralleled wind direction has been presented in the article (see 4.1.1). Moreover, results for all three land use efficiency variants in case of the abovementioned wind direction have been holistically compared (see 4.1.2). Subsequently, a summary of results for this type of building development has been described, using three variants of land use efficiency for three wind directions (see 4.1.3).

The results for other types of buildings, that is, section (see 4.2) and linear (see 4.3) have been described in a synthesized manner, comparing all three variants of land use efficiency for the three wind directions analysed in the study (the description of detailed comparisons of research results has been omitted here). Following that stage, a final comparison of all variants has been presented (see 4.4).

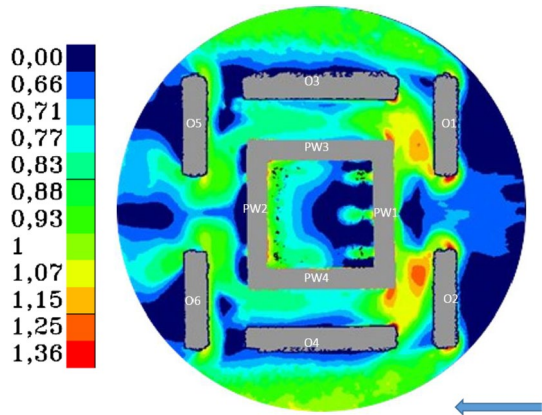
3.1 Results for a single variant—on the example of one of the models

3.1.1 Results for quarter building development with high land use efficiency—paralleled wind direction

Based on the results of visualization study (Fig. 6) and erosion study (Fig. 7), it can be observed that the main airflow reaches the interior of the layout between the O1



Fig. 7 A map presenting distribution of the amplification coefficient obtained as a result of sand erosion technique for quarter building development with high land use efficiency



and O2 buildings. The airflow bounces off the PW1 wall of the main building, which results in the incoming air being slowed down. Next, the main air flow splits into two accelerating streams flowing along the O1 and O2 buildings and falling into the spaces between the main PW building and the O3 and O4 buildings. A large stagnation zone becomes noticeable in the courtyard of the main building, although streams of air that flow in through the gates of the courtyard can be seen. The air is rebounded off the windward side of the PW2 wing, and then moves, gradually slowing in velocity, to the central part of the courtyard. Clear stagnation zones can be observed on the leeward side of the PW building and the O3, O4, O5, O6 buildings. The zones of highest flow velocity appear in the corners of the windward edges of the O1 and O2 buildings and at the windward walls of the main building (PW1), as well as in the spaces between the buildings mentioned. Even when wind velocity reaches values lower than 5 m/s, these zones may prove uncomfortable for pedestrians, as the velocity there is intensified by 25 to 36%.

3.1.2 Comparison of results for quarter building development according to three variants of land use efficiency—paralleled wind direction

Likewise, the airflow for quarter building development with low and medium land use efficiency has been analysed. Following the analysis, the results have been juxtaposed for comparison. When analysing the consolidated summary of the study (Fig. 8), some common features and differences can be observed. The largest stagnation zone inside a courtyard is formed in the case of building developments with medium land use efficiency (due to the fact that the courtyard in this case is the “tightest”, the coefficient equals $W/H = 2.57$). Whereas the weakest stagnation zone occurs in the case of developments with high land use efficiency (W/H ratio of the courtyard = 4.89). Outside the inner area of the courtyard, the largest zone of a low amplification coefficient ($\alpha \in (0.0.66)$) forms also for buildings with medium land use efficiency, while the weakest stagnation zone is visible in the case of building developments with high land use efficiency. The largest areas of intensified flow ($\alpha > 1.25$) occur in vicinity of the windward side of the main building for building developments of high land use efficiency.

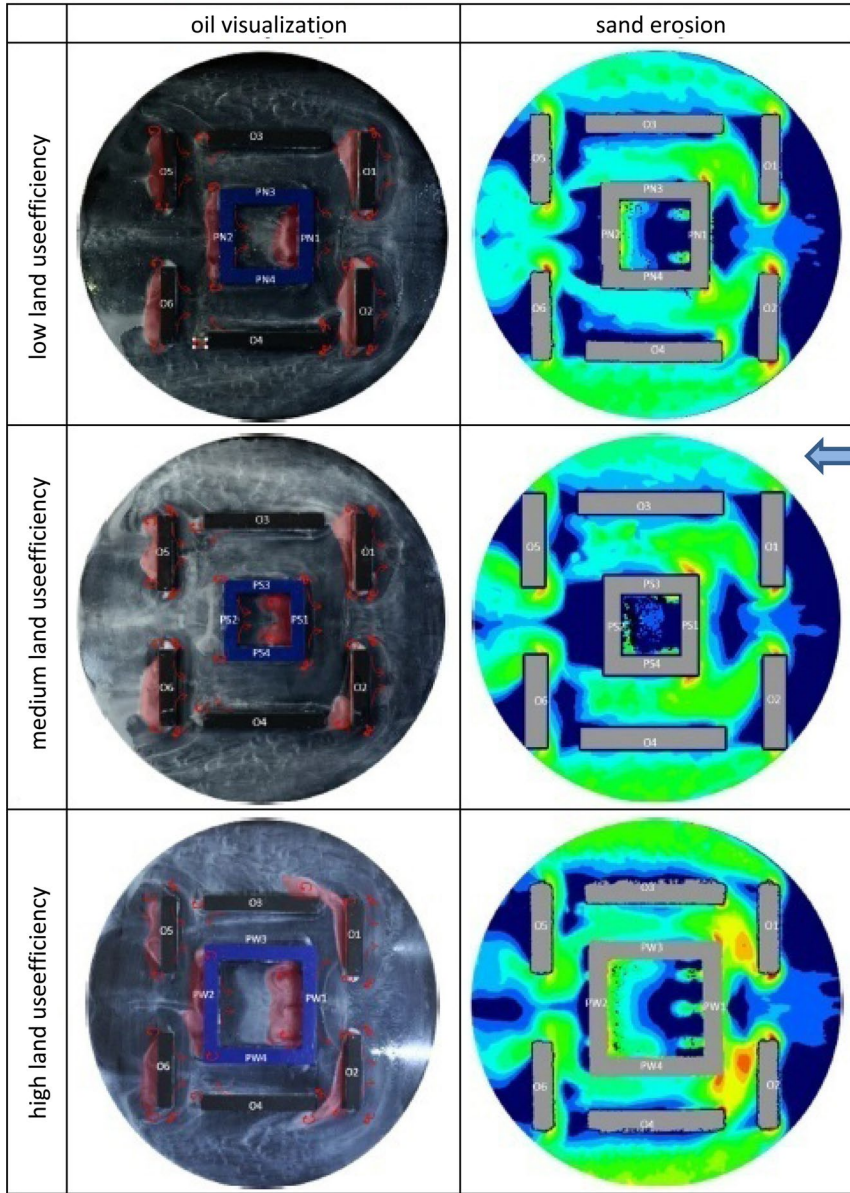


Fig. 8 A comparison of research results obtained with the application of visualization technique and erosion technique for quarter building developments in three variants of land use efficiency - paralleled wind direction

3.1.3 Comparison of results for quarter building development in three variants of land use efficiency—paralleled, perpendicular and oblique wind direction

Similar research has been conducted for perpendicular and the oblique wind directions.

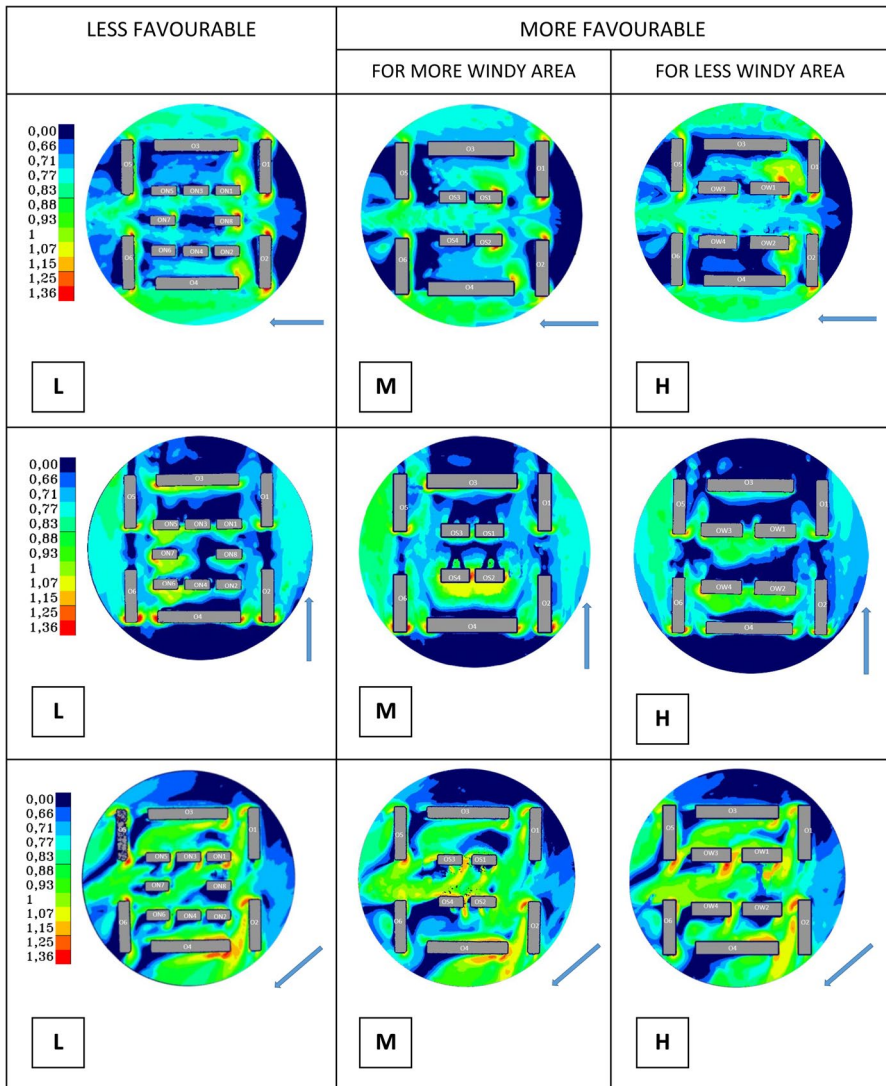


Fig. 9 Comparison of wind conditions around section building development for low (L), medium (M), high (H) land use efficiency. Results obtained using erosion technique for paralleled, perpendicular and oblique wind directions

Certain conclusions have been formulated on the basis of this research. Due to the large number of illustrations, not all the results have been presented in the article in the same manner as the authors described the above case. All results for the erosion technique (the alterations in the flow are more visible thanks to the colours) have been shown in the comparisons in the final results (see 4.4) in Figs. 9, 10 and 11.

Quarter building development with low land use efficiency is characterized in all cases by low level of airiness for the building quarter and for its surroundings. The



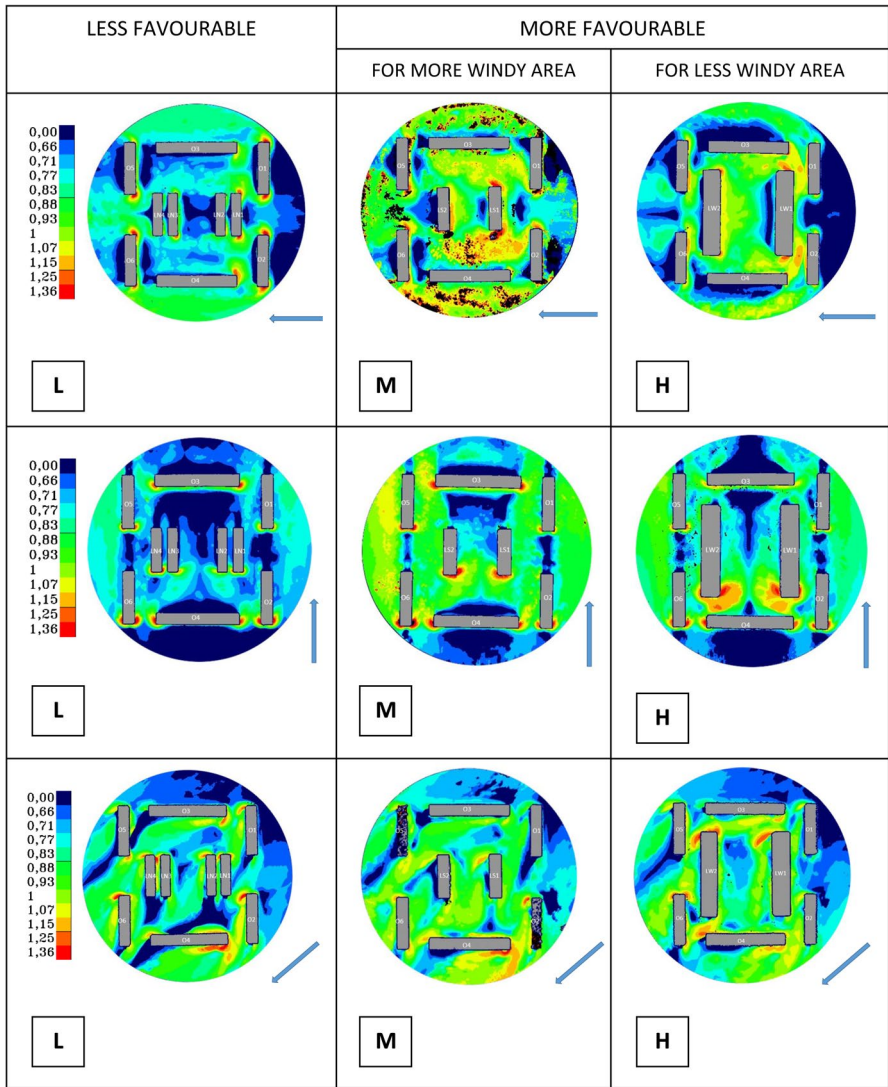


Fig. 10 Comparison of wind conditions around linear building development for low (L), medium (M), high (H) land use efficiency. Results obtained using erosion technique for paralleled, perpendicular and oblique wind directions

courtyard of a quarter building development with a medium land use efficiency is clearly less ventilated, while the space between neighbouring buildings is better ventilated.

In the case of the quarter building development with a high land use efficiency, the courtyard is relatively large and best ventilated, as opposed to the previously discussed variants. Yet, in the space between neighbouring buildings, there exist areas with a higher rate of velocity gain ($\alpha > 1.25$). These areas, however, are not extensive. For areas affected by winds of velocities higher than 4 m/s, a variant with an medium land use efficiency seems more comfortable to pedestrians. Still, if wind velocities in a given area are rarely

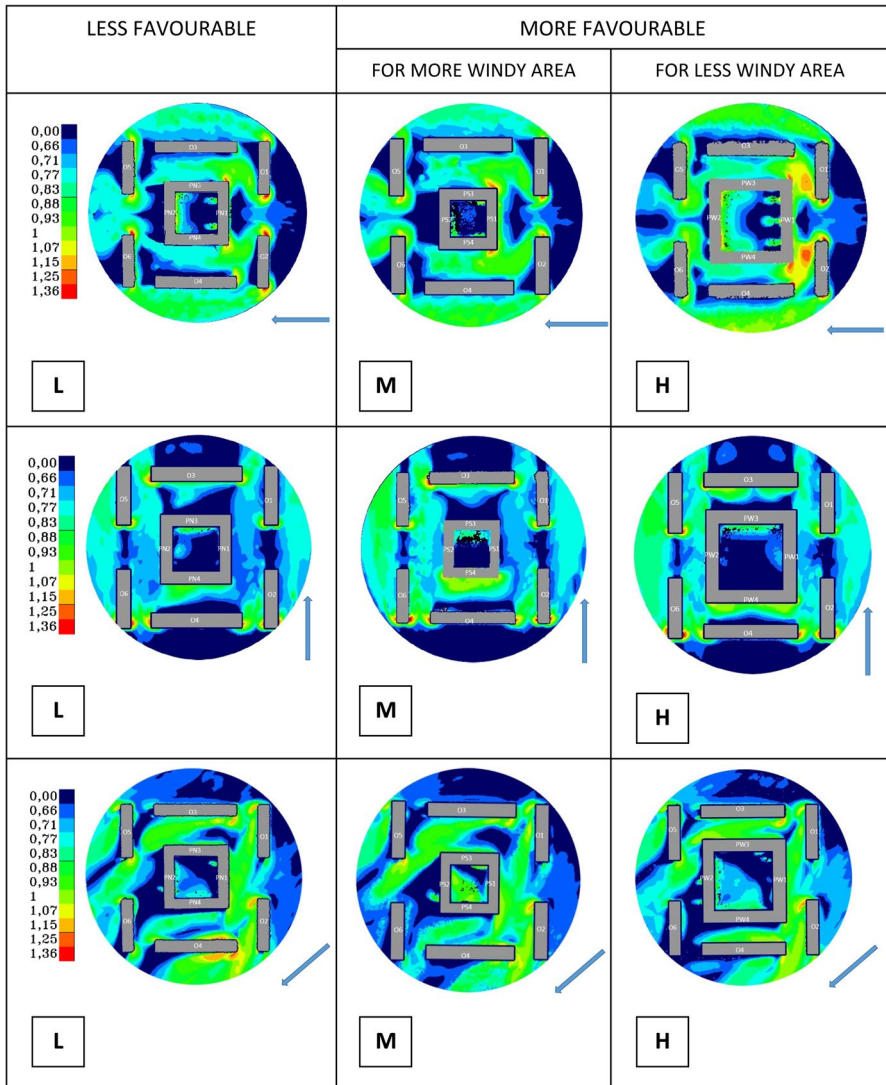


Fig. 11 Comparison of wind conditions around quarter building development for low (L), medium (M), high (H) land use efficiency. Results obtained using erosion technique for paralleled, perpendicular and oblique wind directions

on the increase, quarter building development with high land use efficiency seems the most favourable one, as it offers the best airiness of the entire quarter.

3.2 Comparison of results for section building developments in three variants of land use efficiency—paralleled, perpendicular and oblique wind direction

Analogous tests and comparisons have been performed for section building developments with low, medium and high land use efficiency. Section building development with low

Table 2 A comparison of wind conditions in pedestrian zone for three types of building developments for low, medium and high land use efficiency

Type of development	Wind conditions in pedestrian zone		
	Less favourable	More favourable	
		For more windy areas	For less windy areas
1. Section	Low land use efficiency	Medium land use efficiency	High land use efficiency
2 Linear	Low land use efficiency	Medium land use efficiency	High land use efficiency
3 Quarter	Low land use efficiency	Medium land use efficiency	High land use efficiency

land use efficiency is the least-ventilated one ($W/H=2.67$). Minor differences in reference to layout airiness occur in developments of a medium ($W/H=1.51$), and high land use efficiency ($W/H=2.3$). Whenever a stronger wind is blowing (above 4 m/s), section building development of high land use efficiency turns into a less comfortable layout. This happens due to the occurrence of larger areas with a higher wind amplification factor ($\alpha > 1.25$).

3.3 Comparison of results for linear building development in three variants of land use efficiency—paralleled, perpendicular and oblique wind direction

Linear building development of low land use efficiency ($W/H=1.33$ and 6.22) is quite comfortable for pedestrians. However, as it is in the case of section building developments, linear layout is characterized by poor airiness. The largest zones of the amplification coefficient ($\alpha > 1.25$) appear around high efficiency buildings developments ($W/H=3.11$). Among all types of development layouts, linear building development of medium land use efficiency ($W/H=2.33$) seems the most favourable one, as the area in such case is well ventilated, whereas wind velocity in standard weather conditions does not exceed values uncomfortable for pedestrians. Wind velocity increased by about 36% in relation to the average value of wind velocity ($w=1.36$ v) appears in minor zones on windward sides of the building and at building corners.

3.4 Final results of all the variants comparison

Research conducted with the use of oil visualization and sand erosion methods for all three types of building developments in three variants of land use efficiency have been compared. In all of the layouts, minor areas with an increased amplification factor ($\alpha > 1.25$, which appear mainly at the corners of buildings) are observable, together with less and more extensive stagnation zones. In the building development models tested in the present research, the issue of limited ventilation possibilities poses greater problems than the issue of the wind acceleration that may prove uncomfortable for pedestrians.

Research has shown that selection of the optimal building development layouts, considering various wind directions, is anything but easy. Having analysed the results obtained with the use of visualization and erosion techniques, more and less advantageous configurations have been selected (Table 2). Figures 9, 10, and 11 present visualizations of results obtained by erosion technique.

It has been determined that less favourable wind conditions in the pedestrian zone prevail around building developments of low land use efficiency in cases of section, linear and



quarter building developments. Section building development seems the least favourable one. In this case, the largest areas of reduced velocity have been observed, for instance, ones for which $\alpha \leq 0.66$, mainly due to the presence of a number of buildings in the plot and small spaces between objects. These spaces are rather poorly ventilated and thus belong to potential stagnation zones, where pollution can accumulate. On the other hand, many local spaces where the velocity is amplified by $\alpha > 1.25$ may be noticed. This is linked to the phenomenon of airflow acceleration at building corners. The more blocks of buildings are introduced in the plot, the more local zones of increased velocity appear.

For section and linear building developments, more favourable configurations of medium land use efficiency have been discovered, where the majority of the area is well ventilated, with minor stagnation zones. For the quarter building development, it has been determined that the most favourable layout was the one of a high-efficiency building development, with the largest courtyard and with relatively best air exchange within it.

Having analysed all of the types of building developments, linear building development of medium efficiency seems to be the most favourable one when it comes to wind conditions in pedestrian zone. For all of the wind directions studied in the present research, the observed stagnation zones were rather insignificant. The geometric structure of the linear building development is more open to air inflow than the quarter building developments with closed courtyards. Low-efficiency section building development, on the other hand, has been identified as the least favourable of all types of the layouts tested, as it is the most fragmented one. It also contains the largest number of corners. The results obtained while testing this type of layout have pointed to large zones of poorly ventilated areas where pollution accumulates. An intensified flow was observed at all the edges of the buildings.

4 Discussion

The obtained results were of varied nature and were thus difficult to use for a clear comparative assessment. However, the conclusions derived from the comparison of individual variants of land use efficiency within one type of building development proved more unambiguous. It is worth noting that the obtained detailed results allow for comparisons between any groups of variants. Moreover, the results might prove useful, for example, to draw comparisons between different types of building developments for one variant of land use efficiency. Furthermore, it is valuable to analyse individual variants and see them as the ability to identify specific local phenomena.

It is important to reckon with the fact that when environment layout of a model building development is altered, the test results may differ, though probably not substantially so, assuming that the surrounding building development is compact and encircles the tested area. Problems were observed mainly regarding the layouts in which buildings are located close to each other. Increasing the height of the surrounding building development does not seem to essentially affect the elimination of these problems. On the contrary, such problems may be intensified due to obscuring. Formation of the surrounding building development as a less compact layout open to the inlet of airflow into the studied area might cause a greater discrepancy in test results.



5 Conclusions

The research discussed in the present paper has made it possible to compare wind conditions in the spaces between buildings for three types of housing development for low, medium and high land use efficiency. It should be emphasized that the results concern only theoretical models developed by Pallado [24]. The results indicate that, regardless of the type of building development, more favourable wind conditions at pedestrian level prevail around building developments of medium and high land use efficiency. This happens due to greater height of development layouts, as well as owing to the need to provide a larger amount of undeveloped areas in their vicinity (recreational areas, road layout, car parks).

The results, systematized in groups at various levels of detailedness, provide numerous conclusions that may be useful in making urban planning decisions regarding the use of areas for a specific type of building development and architectural decisions concerning building formation. It seems purposeful to develop this type of research in relation to other types of building layouts characteristic for heavily urbanized areas, as they tend to be affected to the greatest degree by problems in the field of air pollution and summer overheating. The method presented here is relevant in relation to model situations, the analysis of which provides general knowledge. The method is also useful as a support in the design process, but due to its time-consuming nature, it can be used to check selected variants of situations. A stronger integration of wind research with design process would require a proper combination of elements of the above described method with numerical techniques.¹ This approach would allow for faster action, better synchronized with the spatial decision-making process.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

¹ For several cases presented in here, numerical simulations with the use of the ANSYS FLUENT package have been conducted. The results obtained from such simulations proved to be comparable in terms of quality to the experimental research results and they lead to similar conclusions.



References

- Baik J, Kim J (1999) A numerical study of flow and pollutant dispersion characteristics in urban street canyon. *J Appl Meteorol* 38:1576–1589
- Blocken B (2014) 50 years of computational wind engineering. past, present and future. *J Wind Eng Ind Aerodyn* 129:69–102
- Blocken B, Carmeliet J (2004) Pedestrian wind environment around building: literature review and practical examples. *J Therm Envelope Build Sci* 28:107–159
- Blocken B, Carmeliet J, Stathopoulos T (2011) Application of CFD in building performance simulation for the outdoor environment: an overview. *J Build Perform Simul* 4:157–184
- Blocken B, Persoon J (2009) Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard. *J Wind Eng Ind Aerodyn* 97:255–270
- Blocken B, Stathopoulos T, van Beeck J (2016) Pedestrian-level wind conditions around buildings: review of wind-tunnel and CFD techniques and their accuracy for wind comfort assessment. *Build Environ* 100:50–81
- Bottema, M. (1993). Wind climate and urban geometry eindhoven: technische universiteit eindhoven <https://doi.org/10.6100/ir388789>, <https://pure.tue.nl/ws/files/13219080/388789.pdf> Accessed 20 November 2018
- Bottema M (2000) A method for optimisation of wind discomfort criteria. *Build Environ* 35:1–18
- Chen L, Hang J, Sandberg M, Claesson L, Di Sabatino S, Wigo H (2017) The impacts of building height variations and building packing densities on flow adjustment and city breathability in idealized urban models. *Build Environ* 118:344–361
- Conan B, vanBeeck J, Aubrun S (2012) Sand erosion technique applied to wind resource assessment. *J Wind Eng Ind Aerodyn* 104–106:322–329
- Daniels K (1998) The technology of ecological building. Birkhauser, Berlin, pp 78–90
- Dezső G (2006) On assessment of wind comfort by sand erosion. eindhoven: eindhoven University of technology <https://doi.org/10.6100/ir611138>, <https://pure.tue.nl/ws/files/1906103/200610897.pdf>. Accessed 20 May 2019
- Dygulska A, Perłańska E (2015) Mapa wietrzności Polski, Ochrona Środowiska III—projekt czysta energia. Słupsk: Akademickie Centrum Czystej Energii, https://kierunkizamawiane.apsl.edu.pl/pliki/czystaenergia/raport2_II.pdf. Accessed 04 January 2019, (in Polish)
- Gandemer J (1978) Discomfort due to wind near buildings: aerodynamic concepts. Building Research Translation. Washington: National Bureau of Standards Technical Note, pp 710–9
- Gumowski K, Olszewski O, Poćwierz M, Zielonko-Jung K (2015) Comparative analysis of numerical and experimental studies of the airflow around the sample of urban development. *Bull Polish Acad Sci Tech Sci* 63:729–737
- Idem R (2009) What do we learn from alternative forms of shaping housing environment? *Housing Environ* 7:71–77
- Janssen WD, Blocken B, van Hoof T (2013) Pedestrian wind comfort around buildings: comparison of wind comfort criteria based on whole-flow field data for a complex case study. *Build Environ* 59:547–562
- Jędrzejewski M, Poćwierz M, Zielonko-Jung K (2017) The problem of airflow around building clusters in different configurations. *Archive Mech Eng* 44:401–418
- Krauthaim M, Pasel R, Pfeiffer S, Schultz-Granberg J (2014) City and wind. Climate as an Architectural Instrument. DOM publishers, Berlin, pp 71–77
- Köse DA, Dick E (2010) Prediction of the pressure distribution on a cubical building with implicit LES. *J Wind Eng Ind Aerodyn* 98:628–649
- Köse DA, Fauconnier D, Dick E (2011) ILES of flow over low-rise buildings: influence of inflow conditions on the quality of the mean pressure distribution prediction. *J Wind Eng Ind Aerodyn* 99:1056–1068
- Lawson TV, Penwarden AD (1975) Effect of wind on people in the vicinity of buildings. In: Proceedings 4th Int'l conference on wind effects on buildings and structures, Heathrow, UK, pp 605–622
- Murakami S, Mochida A, Hayashi Y (1990) Examining the k-ε model by means of a wind tunnel test and large-eddy simulation of the turbulence structure around a cube. *J Wind Eng Ind Aerodyn* 35:87–100
- Pallado J (2014) Zabudowa wielorodzinna Zasady projektowania. Politechnika Śląska, Gliwice, pp 30–33 (in Polish)
- Peng Y, Gao Z, Buccolieri R, Ding W (2019) An Investigation of the quantitative correlation between urban morphology parameters and outdoor ventilation efficiency indices. *Atmosphere* 10(33):1–17

26. Priyadarsini R, Wong NH (2005) Parametric studies on urban geometry, air flow and temperature. *Int J Architect Sci* 6:114–132
27. Ratti C, Sabatino S, Britter R (2006) Urban texture analysis with image processing techniques: winds and dispersion. *Theoret Appl Climatol* 84:77–90
28. Reiter S (2008) Validation process for CFD simulations of wind around building. In: European built environment CAE conference
29. Richards PJ, Norris SE (2011) Appropriate boundary conditions for computational wind engineering models revisited. *J Wind Eng Ind Aerodyn* 99:257–266
30. SakrFadl M, Karadelis J (2013) CFD simulations for wind comfort and safety in Urban Area: a case study of coventry university central campus. *Int J Architect Eng Construct* 2:131–143
31. Shirzadi M, Naghashzadegan M, Mirzaei P (2018) Improving the CFD modelling of cross-ventilation in highly-packed urban areas. *Sustain Cities Society* 37:451–465
32. Stathopoulos T (2009) Wind and comfort. In: Proceedings 5th European and African conference on wind engineering. Florence, Italy. <http://www.iawe.org/Proceedings/5EACWE/K04.pdf>. Accessed 20 November 2018
33. Stathopoulos T (2011) Introduction to environmental aerodynamics. In: Baniotopoulos CC, Borri C, Stathopoulos T (eds) *Environmental wind engineering and design of wind energy structures CISM courses and lectures*, vol 531. Springer, Venna, pp 3–30
34. Walker R, Shao L, Wolliscroft M (1993) Natural ventilation via courtyards. Part I- theory and measurements. In: Proceedings 14th AIVC conference on energy impact of ventilation and air infiltration. Copenhagen, Denmark, pp 235–250
35. Yoshie R, Mochida A, Tominga Y, Kataoka H, Harimoto K, Nozu T, Shirosawa T (2007) Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan. *J Wind Eng Ind Aerodyn* 95:1551–1578
36. Zhang K, Chen G, Wang X, Mak CM, Fan Y, Hang J (2018) Numerical evaluations of urban design technique to reduce vehicular personal intake fraction in deep street canyons. *Sci Total Environ* 653:968–994

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

