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Orginal Article

Wind aspects in a built-up environment

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Abstract: The dynamic development of built-up areas observed in the last few decades resulted in strong environmental transformations, especially in terms of climate phenomena. One of the factors which significantly affects the climate and bioclimate of urban areas is wind. Wind can cause discomfort to pedestrians or heat loss in buildings, if the wind speed around buildings is too high. The paper presents two examples of research conducted by the author, related to the issues of wind flow in built-up areas, based on the numerical simulations. The numerical simulations become an increasingly frequently used tool to determine the wind climate. Simulation results provide designers with important information on the influence of the buildings and their layout on the local changes in airflow. They allow testing of alternative solutions and effectiveness of various remedial measures.

Keywords: wind, urban structures, comfort, heat loss

1. Introduction

The dynamic development of built-up areas observed in the last few decades resulted in strong environmental transformations, especially in terms of climate phenomena. In addition to natural factors shaping the climate, such as latitude, topography, or the presence of water reservoirs, the anthropogenic factors directly related to human activity have gained in importance. Changes in atmospheric environment and modification of the climate of cities are mostly influenced by:

- intensive emission of pollutants into the atmosphere, related to industrial production, transport or buildings;
- emission of waste heat or heat lost in technological processes and energy devices as well as heat used for heating buildings;
- disruption of natural thermal, humidity and radiation balance due to the large share of artificial substrate (roofs and walls of buildings, street surfaces, etc.) and small amount of greenery;

- decrease in global air exchange with compact buildings and thus increased ground roughness.

Excessive heat, changes in air movement, and changes in the physical and chemical composition of the air have become characteristic features of modern cities.

Such intensive environmental transformations cause the need for decisive measures to improve the quality of life in cities. Implementation of the principles of sustainable development is one of the ways to ensure harmonious growth of urban areas. An important role in this regard is played by the construction industry, recognized as one of the six pioneer markets in the EU, i.e., markets particularly susceptible to innovation and with a high potential for development [1]. Implementation of new technologies and solutions in the construction industry has been considered particularly important due to its impact on the three main pillars of sustainable development – environment, economy, and society. The environmental aspects of sustainable development generally refer to the protection of natural resources, the consumption of which is assessed in relation to the technical life cycle of materials, construction products, as well as the entire building. However, in the context of the development of built-up areas, it becomes more important to extend these issues to additional physical elements affecting the quality of life, i.e., sunlight, ventilation and noise exposure. For example, in the case of dense urban development, the interaction of wind and sun influences the energy efficiency of a particular development layout.

Proper ventilation of built-up areas affecting the improvement of aero-sanitary and microclimatic conditions also becomes extremely important. At the same time, it is worth emphasizing the influence of development on the local wind conditions, which may sometimes lead to sudden increases in velocity and the creation of discomfort conditions for pedestrians. In this context, it is important to consider wind aspects in both land use planning and development design.

2. Wind flow in urban areas

As a result of the city's considerable surface roughness, the wind speed is significantly reduced. Detailed studies of Cracow climate have shown that the reduction of wind speed in the city center is on average 30%, decreasing in the outer zone housing development to 15-20% [2].

Considering the air flow on the scale of housing estate or compact structures of buildings, it should be noted that it is an extremely complex phenomenon. Direction and velocity of air streams are affected by the buildings, their size, layout, as well as the characteristics of the ground and turbulence. Consequently, the changes in wind conditions observed in the urban environment may have a positive or negative character. Unfavourable aspects may include an increase in wind speed near buildings, which can cause discomfort to pedestrians. At the same time, too low wind speeds cause insufficient ventilation of built-up areas and local accumulation of pollutants or snow.

Particularly unfavourable conditions appear in the case of tall buildings [3]. They tend to pull the flow down the walls and create strong turbulence near the ground surface [4]. In addition, the phenomenon of buildings interacting with each other can be observed, revealing disturbances in the pressure and velocity distribution in their vicinity [5, 6]. This results in adverse secondary flows that interfere with pedestrian comfort [7, 8].

Air movement in an urban area is a very complex phenomenon. The largest flow disturbances occur in the ground zone, where variable wind speed field and secondary flows are observed, forced by existing building masses. Changes in the horizontal profile are observed at a distance equal to ten to fifteen times the height of building, while in the vertical profile they reach up to three times the height of building [9]. The most important parameters shaping the airflow in built-up areas include: building length, width and height (L, W, H), direction of the inflowing airflow, z_o and $z_{o,loc}$ roughness parameters and thermal parameters. Despite many factors influencing the wind flow in the vicinity of a building, in each case it is possible to distinguish some characteristic flow zones with different degrees of influence.

As the wind flow approaches the building the air stream is separated and flows around the building (Fig. 1). The air flowing down the upwind wall creates a strong vortex at the ground level. Along the edges of windward wall, the air stream is broken off. The air flowing towards the building base forms vertical vortices, which after reaching the edge of a wall, along which there is a high negative pressure, experience acceleration creating strong side streams [4].

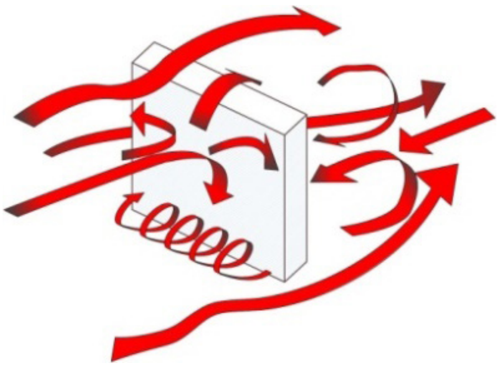

Fig. 1. Wind flow pattern on the windward side of the building. Adapted from [4]

Overcoming the obstacle involves the loss of part of the momentum, thus a zone of reduced flow is created behind the building. Part of the air flowing over the building returns, creating a recirculation zone, and part flows further, creating a far wake zone. Just behind the building, along the vertical edges of leeward wall, a system of vertical vortices forms, a so-called shear layer (Fig. 2.) [4].

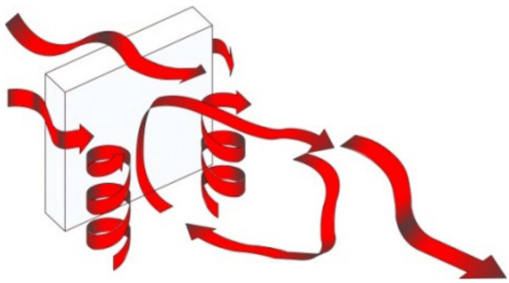

Fig. 2. Wind flow pattern on the leeward side of the building. Adapted from [4]

The Venturi effect occurs when two rows of buildings are located at an angle of less than 90° (Fig. 3). The length of buildings should not be less than 50 m and their average height not less than 15 m. The condition for the effect to occur is also the width of a gap between the buildings (1/2H < gap width < 4H) [10].

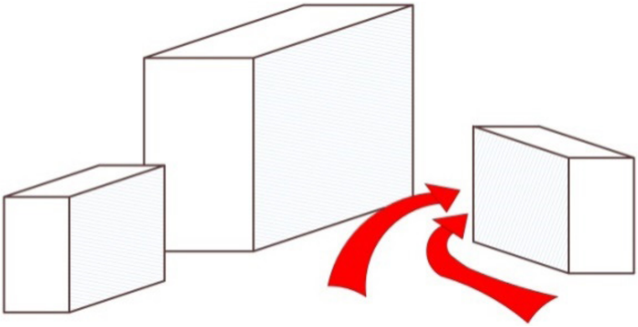

Fig. 3. The Venturi effect. Adapted from [4]

This arrangement of buildings affects the smooth change of flow cross-section which, depending on the wind direction, can cause an increase or decrease in velocity, without the formation of vortices. The increase of wind speed in the constriction is proportional to the height of buildings. For buildings 25 m high, the acceleration factor (defined as the ratio of velocity in the considered building system to the velocity at the same height, measured in the open area) is 1.3, and for buildings 45 m high the factor reaches the value of 1.6 [11].

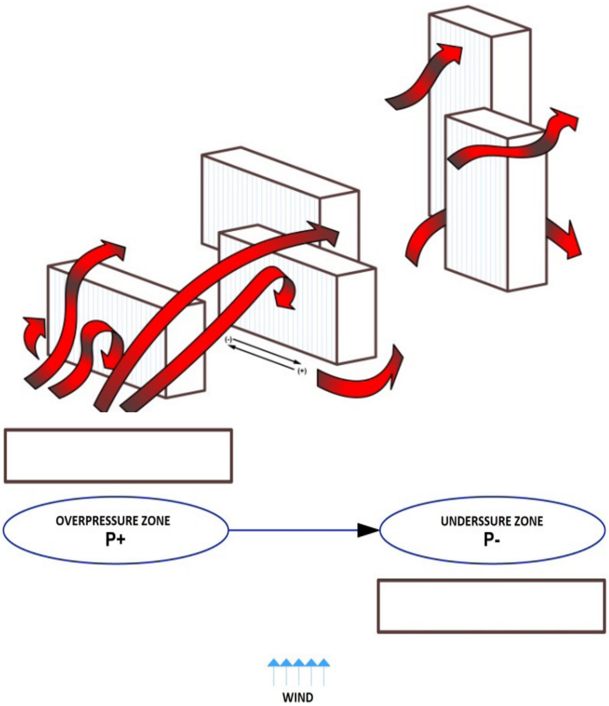

Fig. 4. Schematic representation of wind flow for two parallel buildings shifted towards each other. Adapted from [12]

Another effect, often observed in housing development, is the combination of overpressure and under pressure zones (Fig. 4). This effect occurs in the case of buildings arranged in parallel and additionally shifted in relation to each other. The pressure differences in the building walls result in an acceleration of the air flow from the overpressure zone towards the under-pressure zone. Research conducted by Beraneka in a wind tunnel and cited by Blocken in [12] indicates that pressure differences may be the cause of formation of extensive zones characterized by arduous wind conditions. The acceleration factor in these cases exceeds 2.0. The wind direction also deviates and remains parallel to the longer wall of buildings even at a considerable distance from the building.

The downwash vortex effect (Fig. 5) occurs when two buildings with distinctly different heights and a short distance apart (comparable to the height of the lower building) are adjacent. When the wind is perpendicular to the axis of buildings, there is a vortex of airflow in the zone between buildings, and near the corners of tall building, the air velocity increases significantly. Between the buildings, the acceleration factor can reach a value of 1.5-1.8 [13]. Side streams of a tall building show up to 96% increase in flow velocity [10].

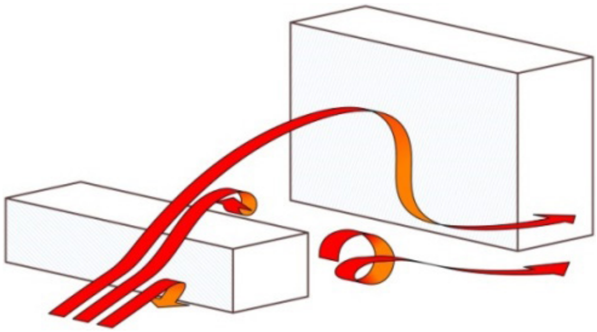

Fig. 5. The downwash vortex effect. Adapted from [4]

The characteristic flow zones around a single building presented above and the basic aerodynamic effects caused by the wind on buildings are disturbed for more complex building structures. Interaction of buildings with each other causes overlapping of individual zones. The result is the appearance of secondary flows, characterized by variable direction and velocity. In some cases, the wind direction changes to the opposite direction, which may cause unexpected feelings of discomfort.

3. Wind conditions at pedestrian level in complex urban structures

Wind flow in urban environment is characterized by sudden changes in directions and speed. In complex urban structures they are sometimes difficult to predict. There is a need for detailed analysis of wind conditions in the early stage of urban design. Numerical methods modelling wind flow around buildings become the useful tools for these purposes [14], [15], [16], [17]. A well-designed urban space should provide adequate ventilation and on the other hand protect pedestrians against too strong air flow.

The example of wind flow analysis from the pedestrian's comfort point of view has been presented below. In the analysed case the numerical simulation allowed to determine the areas of discomfort, where an excessive increase in wind speed was observed. To improve wind comfort in the vicinity of the buildings few kinds of shelter have been proposed.

The analysed building complex is located in the suburb of Warsaw. The buildings form two distinct interiors (Fig. 6). The layout of the buildings causes unpleasant air flows, especially in winter. On the west and south sides, the surrounding area is flat with single low obstacles. Adjacent buildings of similar height are located 150 m and 50 m away from the north and east respectively.

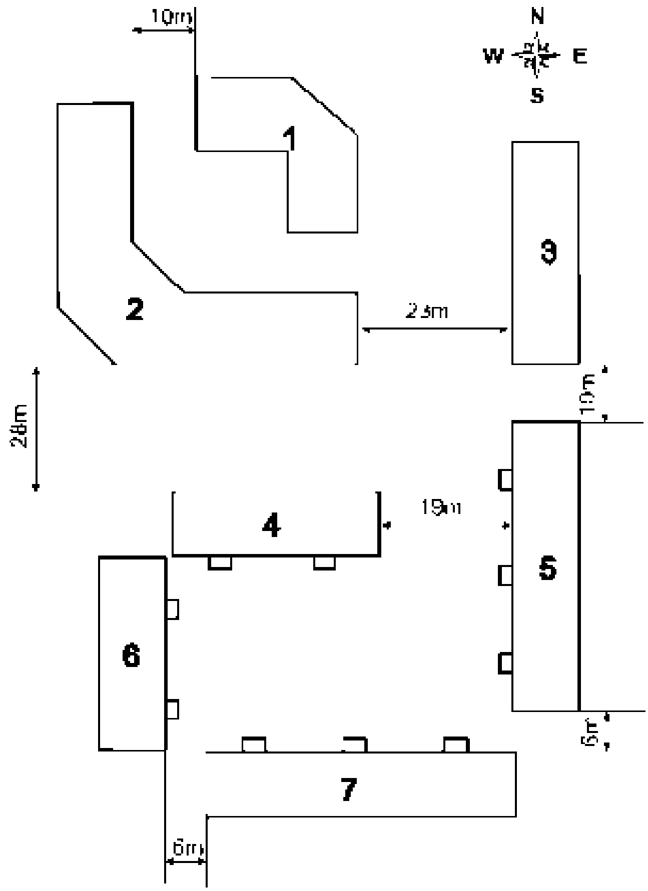

Fig. 6. The arrangement of buildings [18]

The analysis has been done for 8 wind directions and average wind speed for Warsaw, obtained over a 10 year period. Because pedestrians' comfort was the focus of the numerical simulations, wind speeds were analysed at a height of 1.8 m (pedestrian's height). The results were presented in the form of acceleration factor (V/V_o).

Wind flow analyses confirmed the presence of discomfort zones. For example, in the case of the west wind direction dominating in Warsaw the highest value of V/V_o reaches 1.8 were observed in the large canal formed between two interiors (Fig. 7). On the other hand, upstream buildings block the approaching wind and create a shelter zone inside the complex. Detailed information about wind flow pattern in the case of other wind direction can be found in [18].

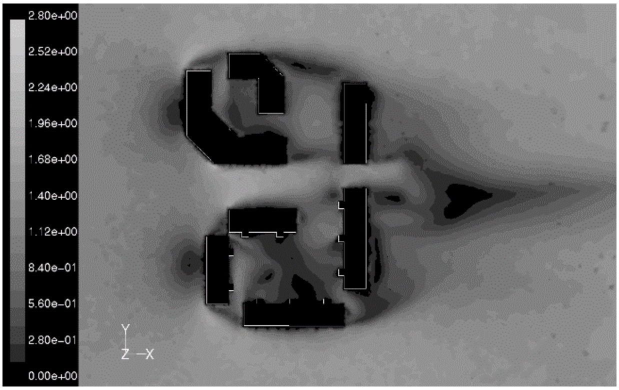

Fig. 7. Wind speed ratio for west wind direction [18]

To weaken the air flow, three types of windbreaks have been proposed: earth berm, acoustic screen, and shelterbelts. Location of windbreaks have been presented at the Figure 8a and 8b.

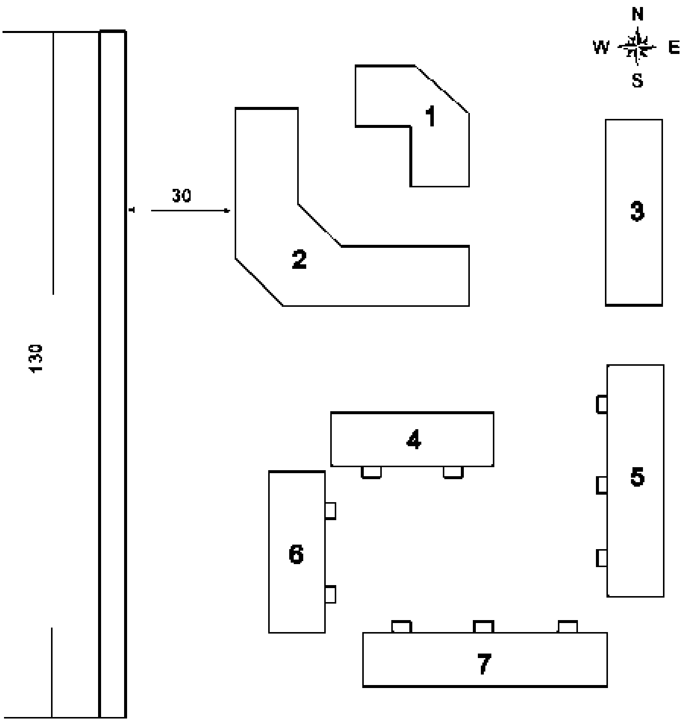

Fig. 8a. Location of the windbreaks and trees [18]

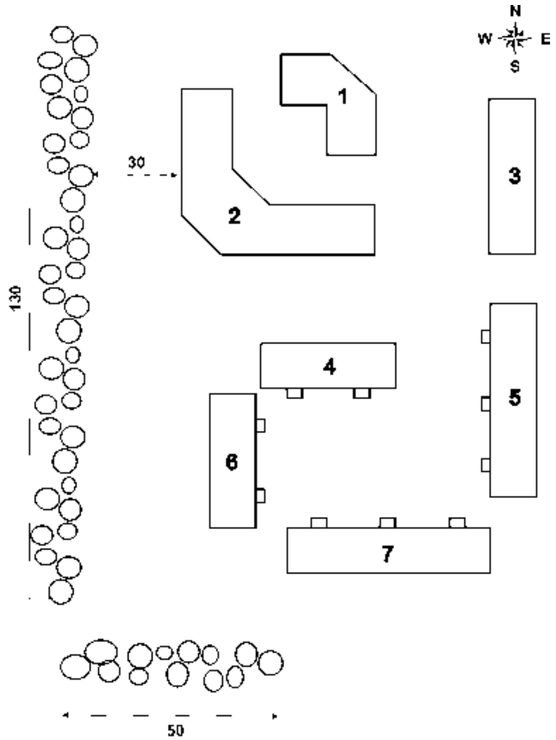

Fig. 8b. Location of the shelterbelts 2 [18]

Two kinds of shelterbelts have been considered. In the first case (shelterbelt 1) a row of trees was located as on the Fig. 8a. In the case of (shelterbelt 2) an additional row of trees has been introduced as a protection from the southwest winds (Fig. 8b).

Shelterbelts modelled in the simulation consisted of trees and shrubs. It allowed to reach a higher effectiveness. The dimensions of the shelterbelt were: 130 m x 7 m x 10 m (width, height, length). Two shapes of the crown have been included: cone – shaped crown representing a conifer and ball – shaped crown stands for a deciduous tree.

The earth berm was the next analysed case of windbreak. Its dimensions were: 130 m x 4 m x 10 m (width, height, length). To allow for additional plantings, the top of the earth berm was assumed to be flat.

As the building complex is adjacent to the street with traffic density of about 1000 vehicles per hour, an acoustic screen has been proposed to protect the residents from noise and wind. The acoustic screen was located in the western side of the building complex. Its dimensions were: 130 m x 4 m x 0.25 m (width, height, length). In that case the effectiveness of noise barrier in reducing sound levels is about 15 dB.

In the case of wind inflow from the west direction, all kinds of windscreens reduced air flow in a canal between two interiors. (Fig. 9). Near the upstream corners of the buildings maximum value of V/V_o changes from 1.7 to 1.46.

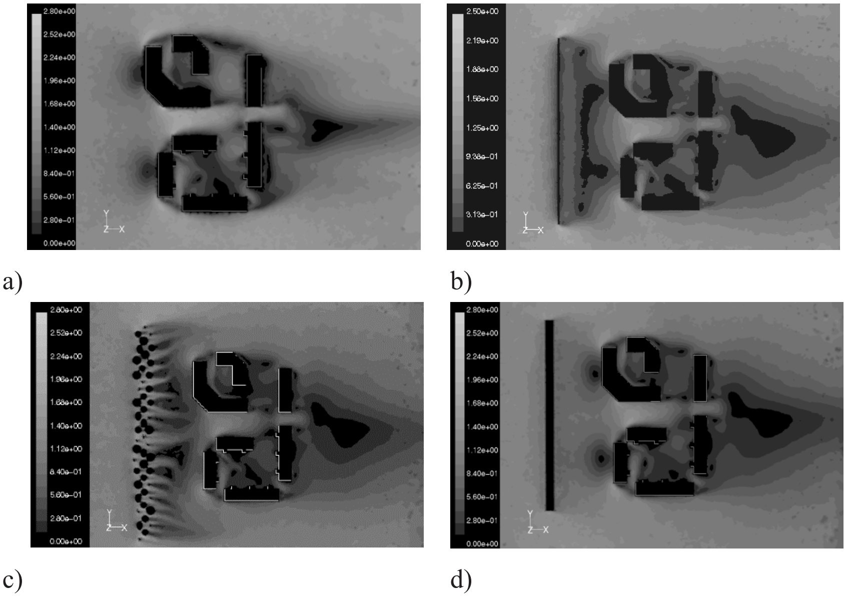

Fig. 9. Wind speed distribution in analysed complex: a) without shelter, b) with acoustic screen, c) row of trees and d) earth berm [18]

Distribution of V/V_o in the passage between buildings 2 and 4 for all analysed cases has been shown on Fig. 10. The use of wind screens, regardless of their type, brought the desired effect. The maximum reduction in V/V_o, about 0.7 have been achieved for shelterbelts both with one and two rows of trees.

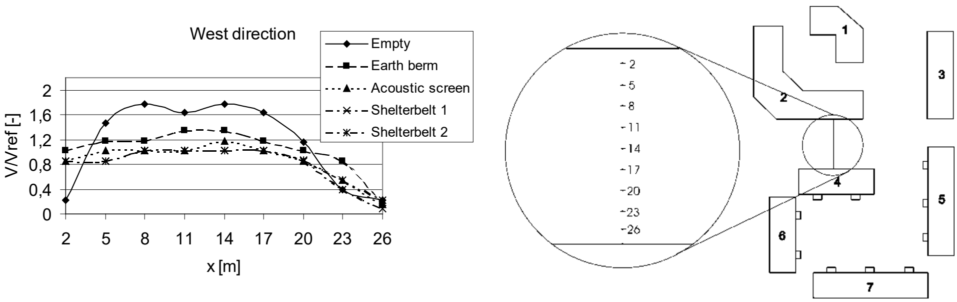

Fig. 10. Distribution of V/V_o ratio in the corridor between buildings 2 and 4 for different windbreaks and west wind direction [18]

In the case of southwest wind direction, the pedestrians' comfort is seriously affected, especially in the passage between buildings 6 and 7. Application of windbreak partially reduced the wind speed in this area. Figure 11 shows distribution of V/V_o ratio in the analysed narrow passage.

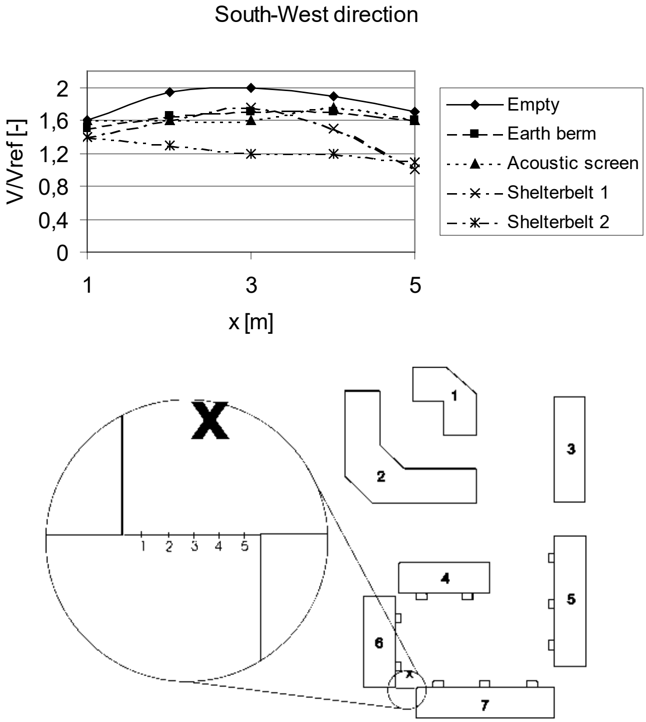

Fig. 11. Distribution of wind speed ratio V/V_o in the passage between buildings 6 and 7 for different windbreaks and south-west wind direction [18]

The best results were obtained for the shelterbelt 2. Additional row of trees in the southwest part of the buildings complex reduces wind speed ratio about 0.6. To check the efficiency of individual shelterbelts in the case of different wind directions, wind speed ratio was determined in a selected point located in the most affected zone (Fig. 12). Location of that point is shown on Figure 11.

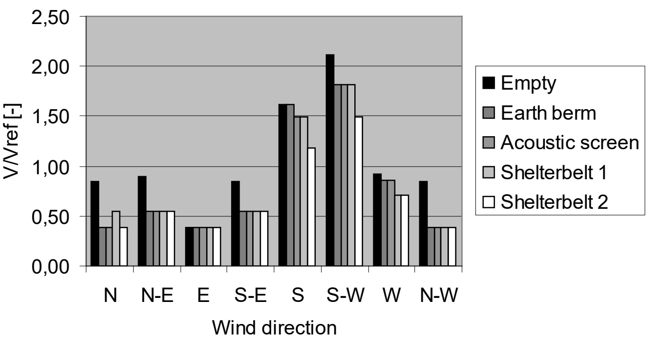

Fig. 12. Wind speed ratio in the analysed point for different wind direction [18]

The evident influence of shelterbelt 2 on wind speed reduction can be observed for almost all wind directions. Only in the case of the west and east winds the effect was relatively small. Shelterbelt 2 consisting of two rows of trees gives the best protection among all considered types of wind screens when wind flow from west and southwest directions. In the corner streams of the upstream buildings wind speed ratio changes from 2 to 1.62.

4. The effect of wind load on conduction heat loss in buildings

One of the factors describing heat exchange on outer surface of building envelopes is wind. In complex urban environments wind speed varies depending on layout of the buildings and their geometric parameters. Therefore, the appropriate estimation of its value in the nearest proximity of a building envelope is critical for energy simulation purpose. Numerical simulation could provide detailed information about wind speed distribution near buildings. In order to illustrate the influence of wind on heat loss, CFD analyses of wind flow around a multifamily building have been made. The obtained results were then used as input data for energy analyses.

The analysed building is a part of a small urban complex located in the suburbs of Warsaw. Figure 13 presents the location of the building.

It is a typical, forty years old, ten floor concrete building with balconies on the western elevation. Thermal properties of external partitions are rather poor, where values of heat conduction coefficient equal 1.14 W/m^{2}K for walls and 2.6 W/m^{2}K for windows. Furthermore, the joints of elements (windows-slab and slab-slab) are imprecise and caused greater heat losses by infiltration.

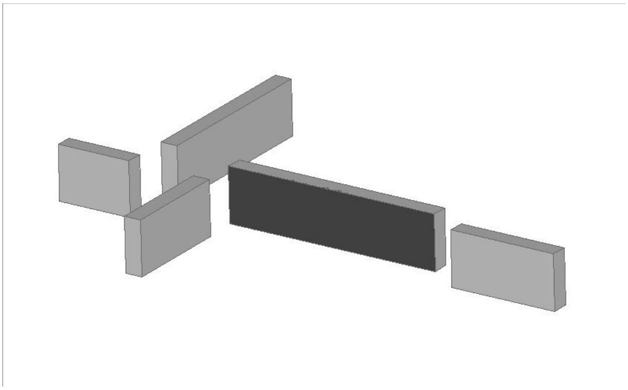

Fig. 13. Prospective model view of the analysed building and its surrounding [19]

As a result of numerical simulation wind speed distribution data around analysed building was obtained. Figure 15 presents zones of different wind speed at 3 m height for west, dominated wind direction. Additionally, the wind speed was estimated in the selected control points at 1m distance from the western wall. The side points were situated at 2 m intervals from the edges; the upper ones at 1.5 m and the bottom ones at 3 m. The location of the control points has been shown in Fig. 14.

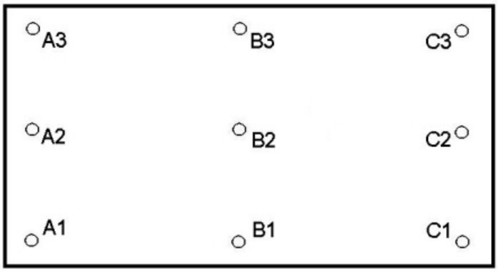

Fig. 14. Control points location [19]

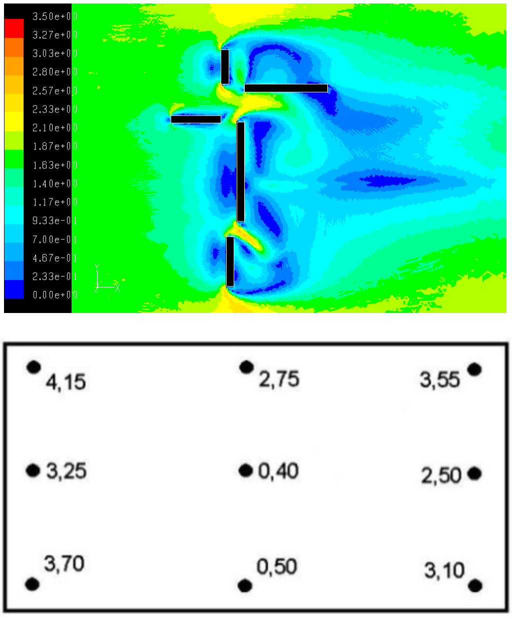

Fig. 15. Flow field and the values of wind speeds [m/s] for west wind direction [19]

In the case of the western flow direction perpendicular orientation of the building reduces the wind flow. The lowest wind speeds occur in the middle of the windward face. Near the corners of the building the wind accelerates. The wind speed ratio V/V_o (the ratio of the mean wind speed V at the 3 m height to the reference wind speed at the same height) reaches 2.5.

The CFD results show considerable differences in wind speed distribution in vicinity of the external wall in a 10-story building. The magnitude of air velocity varies from 0.40 m/s in the central parts of the wall to 4.15 m/s in the top corner Fig. 15).

For the purpose of energy analysis the numerical model has been created with ESP-r (Environmental System Performance) tool [20]. Detailed description of numerical procedure has been discussed in [19].

First, simulations were conducted for the maximum and minimum value of wind speed reported from CFD simulation in the nearest surrounding of the west elevation. Initial calculations showed that the maximum heat flux difference in the middle of the night (the highest temperature difference) is 216 W/m^2 (about 30%) (Fig.16).

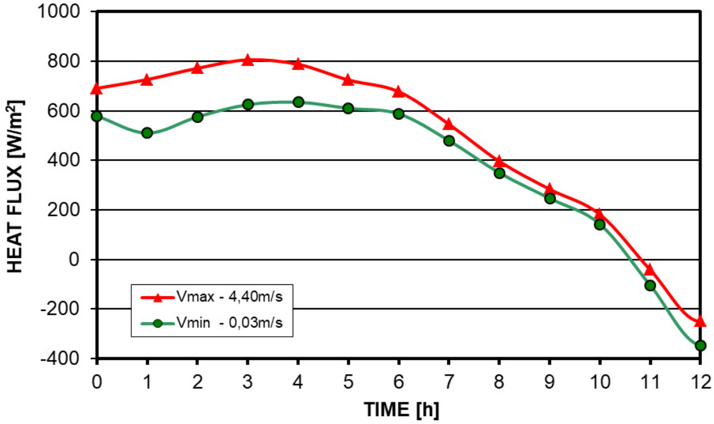

Fig.16. Heat flux for minimum and maximum wind speed from west direction [19]

Subsequently, the conduction heat flux has been calculated for each characteristic point on the elevation. The results for 12 hours are presented in Figures 17-19. They were compared with heat fluxes calculated for wind speed in an open area, estimated on different levels according to wind profile. The assumed winds speed equal 2.39, 3.90 and 4.64 m/s on 1, 2 and 3 levels respectively and are indicated by index V_o.

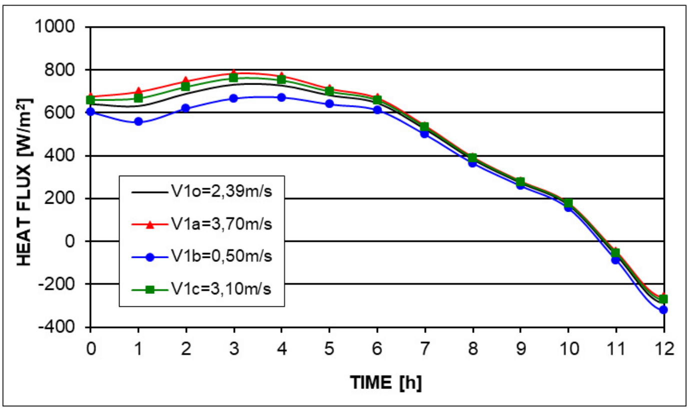

Fig. 17. Heat flux for west wind direction (Fig. 15) and speeds values estimated at points 1A, 1B and 1C compared with initial value 2.39 m/s [19]

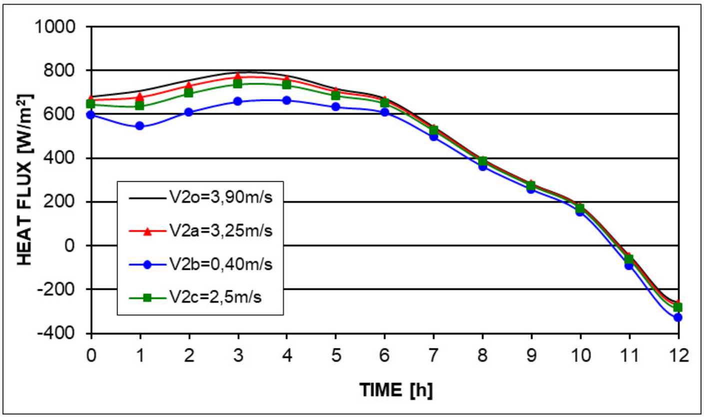

Fig. 18. Heat flux for west wind direction (Fig.15) and speeds values estimated at points 2A, 2B and 2C compared with initial value 3.90 m/s [19]

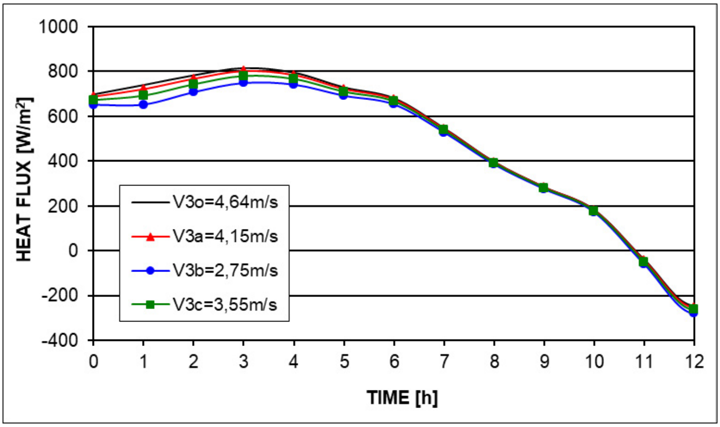

Fig. 19. Heat flux for west wind direction (Fig.15) values estimated at points 3A, 3B and 3C compared with initial value 4.64 m/s [19]

The results for the bottom level, where some local perturbations were detected, show the biggest horizontal differences (Fig. 17). It results from local acceleration or deceleration around the building. In the analysed case, the west wind induces some acceleration especially on the left-hand side of the wall. It caused considerable increase in conduction heat flux on the external surface. On the other hand, the heat losses in the zone located on the middle-low part of the building are much lower (about 25%) than for the zones on the top and the corners. Additionally, the central part of the wall shows the biggest vertical differences in heat flux (Fig. 17-19). Relatively, small differences in wind speed and heat flux (Fig. 19) were reported on the upper level – 1.5 m under the roof edge (about 10%).

5. Summary

The need for favourable wind conditions in a built-up environment is increasingly recognized by the architects and urban planners. Air flow around buildings and its effects are important from the point of view of comfort of people living in their vicinity, as well as the urban ventilation and heat losses in buildings.

Numerical simulations become an increasingly used tool to determine the wind climate. Simulation results provide designers with important information on the influence of buildings on local wind conditions. They allow testing of alternative solutions and, in relation to multi-criteria optimization, searching for solutions which are the most beneficial from the point of view of the adopted assumptions.

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