TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CIVIL ENGINEERING | BUDOWNICTWO

2-B/2016

DOI: 10.4467/2353737XCT.16.160.5771

PIOTR KRAJEWSKI*, ŁUKASZ FLAGA*, ANDRZEJ FLAGA**

WIND TUNNEL TESTS OF WIND VELOCITY AROUND BOX-SHAPE SOLIDS WITH RESPECT TO POSSIBLE FAVOURABLE PLACEMENT OF WIND TURBINES

BADANIA W TUNELU AERODYNAMICZNYM PRĘDKOŚCI WIATRU WOKÓŁ PROSTOPADŁYCH BRYŁ BUDYNKÓW W CELU OKREŚLENIA MOŻLIWIE NAJKORZYSTNIEJSZEGO UMIEJSCOWIENIA TURBIN WIATROWYCH

A b s t r a c t

The paper presents a set of wind tunnel tests performed for four box-shape solids. The tests were performed in a wind tunnel with a modelled boundary layer. The main objective of the research was to determine the mean wind velocity and turbulence at selected points. Potential placement of wind turbines is considered for those points. The paper includes a description of measurement, tests results and analysis of the results. Conclusions contain determination of necessary conditions for the best setup.

Keywords: wind tunnel tests, box-shape solids, wind turbines, wind speed, turbulence

S t r e s z c z e n i e

W niniejszym artykule przedstawiono wyniki badań przeprowadzonych w tunelu aerodynamicznym na czterech prostopadłościennych bryłach budynków. Ich celem było określenie prędkości oraz turbulencji wiatru w określonych punktach wokół poszczególnych brył. We wskazanych punktach modelowych budynków rozważa się bowiem możliwość sytuowania siłowni wiatrowych. Artykuł zawiera opis eksperymentu, wyniki badań, a także ich analizę. Podsumowanie zawiera ponadto prezentację kryteriów niezbędnych w celu wykorzystania pełnego potencjału poszczególnych siłowni.

Słowa kluczowe: tunel aerodynamiczny, prostopadłościenne bryły, turbiny wiatrowe, prędkość wiatru, turbulencja

* M. Sc. Eng. Piotr Krajewski, Prof. D.Sc. Ph.D Andrzej Flaga, Wind Engineering Laboratory, Faculty of Civil Engineering, Cracow University of Technology.

** Ph.D. Łukasz Flaga, Department of Technology of Building Processes and Materials, Faculty of Civil Engineering, Częstochowa University of Technology.

1. Objective of the study

Wind turbines are mainly placed in exposed terrain due to favourable wind conditions. However, numerous studies, e.g. [1, 4, 8, 12, 13], show that, despite the relatively high turbulence and low wind speed, it is justified to place small wind turbines in an urban area. An idea of using renewable sources of energy within sustainable buildings demands different conceptions of architectural design for such turbines. The best places for wind turbine localisation are roofs and narrow spaces between buildings.

Shapes of the tested buildings were determined by authors, taking into account suggestions of the architects. The aim of this study was to measure the wind speed at selected points around the four models of buildings and to determine the best setup for a wind turbine. The tests were conducted in a boundary layer wind tunnel of the Wind Engineering Laboratory at the Cracow University of Technology. The measurements were conducted with thermo-anemometric probes and a hot – wire anemometer system. Justification for experiments and methodology of investigations are based on [5, 10].

2. Theoretical basis of the analysed problem

Descriptions of symbols, parameters and their adopted values used in further considerations are presented in Table 1 and Table 2 [9].

Table 1

Basic physical quantities and adopted values

Name	Symbol	Value
Air density	ρ	1.205 [kg/m^3]
Ambient temperature	t	20.0 [°C]
Reference height	z_{ref}	0.3 [m]
Wind velocity	$\overline{v} = \overline{v}(z_{ref})$	10 [m/s]
Coefficient of dynamic viscosity	μ	1.8369247 * 10^{-5} [Pa*s]

Table 2

Symbols and formulas of other physical quantities

Name	Symbol/formula
Wind turbulence	$I_v = \frac{\sigma_v}{\overline{v}}$

Wind profile	$\bar{v}(z) = \bar{v}(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha}$
Values for power-law exponent α adopted in accordance with [11] are as follows:	
A – open area with few obstacles	$\alpha = 0.14$
B – suburban area with buildings up to 10 m height or forested area	$\alpha = 0.19$
C – urban area with buildings higher than 10 m	$\alpha = 0.24$
where: σ_v –standard deviation of wind speed, $\bar{v}$ mean wind velocity, α – an exponent depending on form and roughness of the terrain, z – height above ground	

2. Experiment description

2.1. Geometry of tested models and location of measurement points

The main objective of the research was to determine the mean wind velocity and turbulence at selected points. Potential emplacement of wind turbines is considered for those points. Shape and scale of the models was specified by the research team. The models of solids used during tests are presented in Fig. 1.

a)

b)

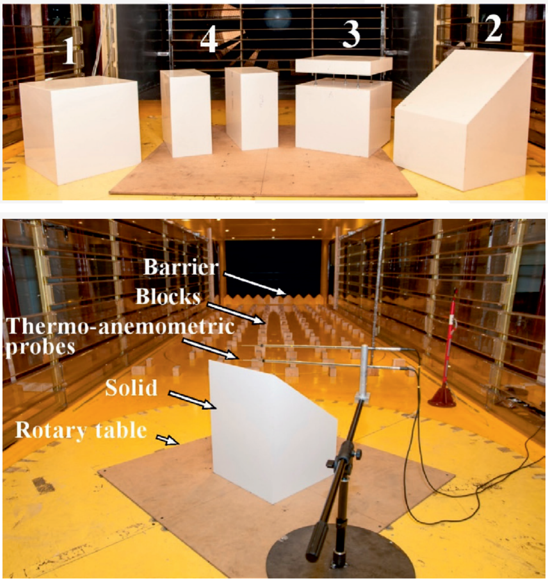


Fig. 1. The models of solids used during tests (a) and elements of the measurement system inside the wind tunnel working section (b)

Based on preliminary arrangements, a set of points with theoretically the best characteristics of exposure due to a wind action as well as its architectural value was chosen. Figure 2 presents each model dimensions and configuration of measurements points.

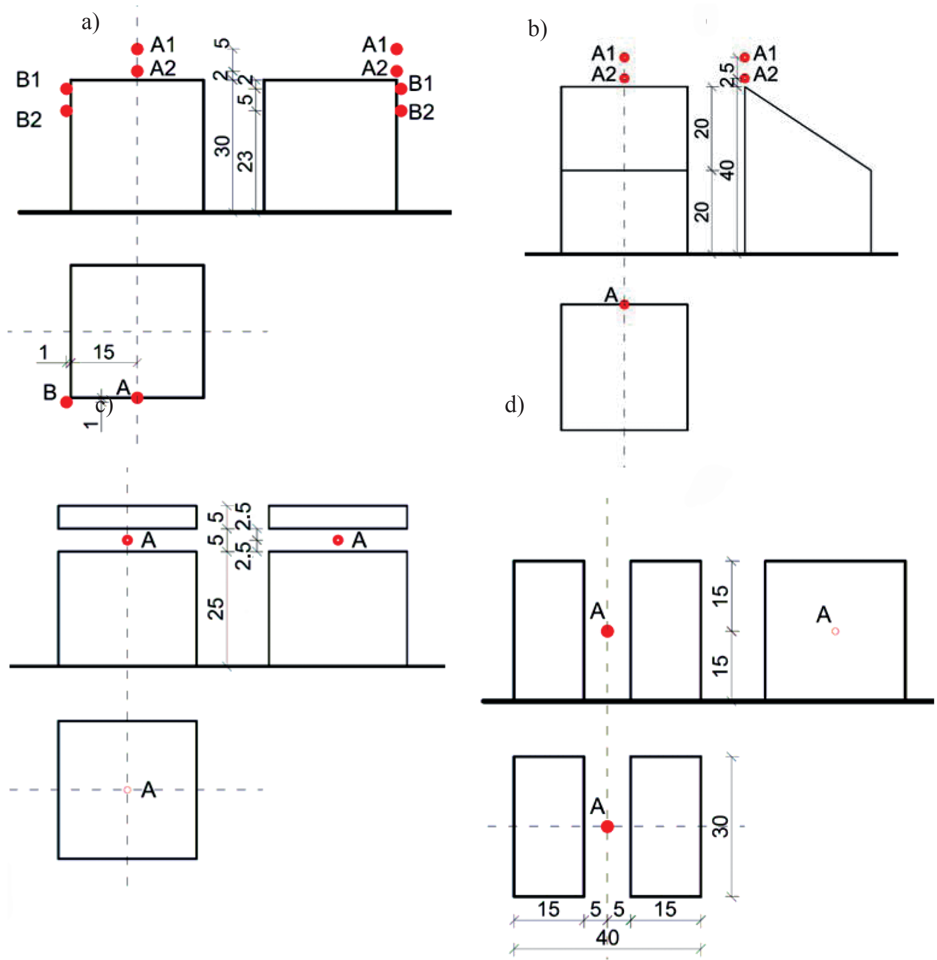
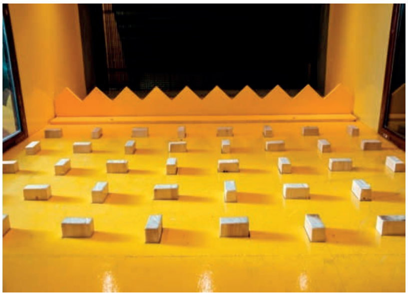


Fig. 2. Model dimensions and configuration of measurements points for: Solid 1 (a), Solid 2 (b), Solid 3 (c), Solid 4 (d) (dimensions given in [cm]). Highlighted points indicate places for turbines

2.2. Terrain roughness category assumed in tests

The terrain roughness category II according to Eurocode 1 [9] was assumed. Due to the assumed location of the buildings in an urban area, the level of turbulence was set up at 17%. Fig. 3.3a shows the barrier and blocks – elements simulating the boundary layer responsible for the received turbulence level. Fig. 3b shows the wind profile obtained for the study. Measurements were carried out for $\overline{v}(z_{ref}) = 10$ m/s wind speed. It was assumed that the reference height for each Solid is the same.

a)



b)

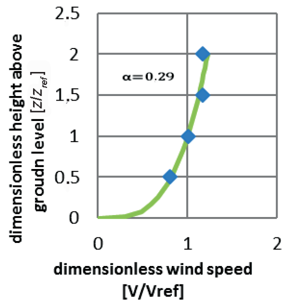


Fig. 3. Elements simulating the boundary layer (a) and wind profile obtained for the study (b) – description in the text

2.3. Fulfilment of similarity criteria

The tested models of box-shape buildings have sharp edges. Therefore, the influence of Reynolds number on the flow around phenomena in a wide range of wind speed is of less importance and can be neglected. In such case of experiments, influence of Mach number, Strouhal number and Froude number can be also neglected.

The most important similarity criteria in this study are geometrical criteria and criteria connected to inflowing air (i.e. profiles of mean wind speed as well as profiles of wind speed turbulence). The set up of conducted tests fulfils these criteria.

2.4. Detailed description of tested cases

For each solid, every direction of inflowing wind was taken into account with an increment of 300. Study case for Solid 1 included 4 measuring points. Due to a location of each pair of measurement points – on the planes of symmetry – this case required test of only 7 different directions of inflowing air (see. Fig. 2a, 8, 9a). View of the Solid 1 during tests is presented in Fig. 4.

Fig. 4. Solid 1 during wind tunnel tests with the measurement system

Study case of Solid 2 included 2 measuring points. Due to the location of the measurement points – along the plane of the elevation and with no symmetry plane – this case required test for 12 different directions of an air inflow (Fig. 2b and 10a). A view of the Solid 2 during tests is presented in Fig. 5.

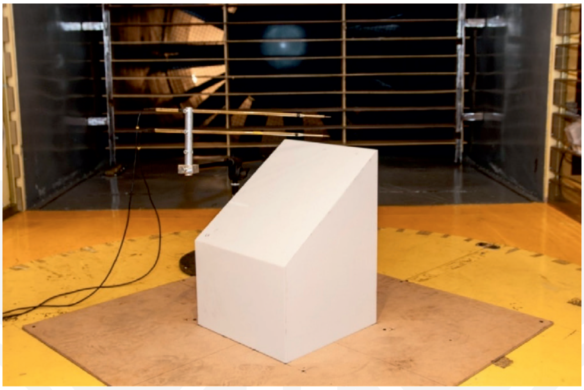


Fig. 5. Solid 2 during wind tunnel tests with the measurement system

Study case of Solid 3 included 1 measuring point. Due to the location of the measurement point – at the intersection of two planes of symmetry – this case required the examination only for 4 directions of the wind inflow (Fig. 2c and 11a). A view of the Solid 3 during tests is presented in Fig. 6.

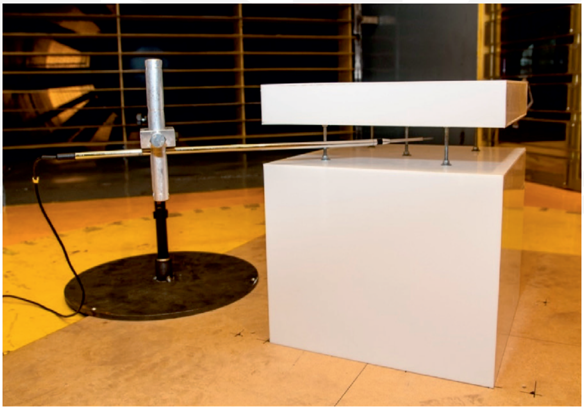


Fig. 6. Solid 3 during wind tunnel tests with the measurement system

Study case of Solid 4 included one measuring point. Due to the location of the measurement point – at the geometrical centre of both sub-solids i.e. at the point of intersection of all three planes of symmetry – this case required a test for only 4 directions of the wind inflow (Fig. 2d and 12a). A view of the Solid 4 during tests is presented in Fig. 7.

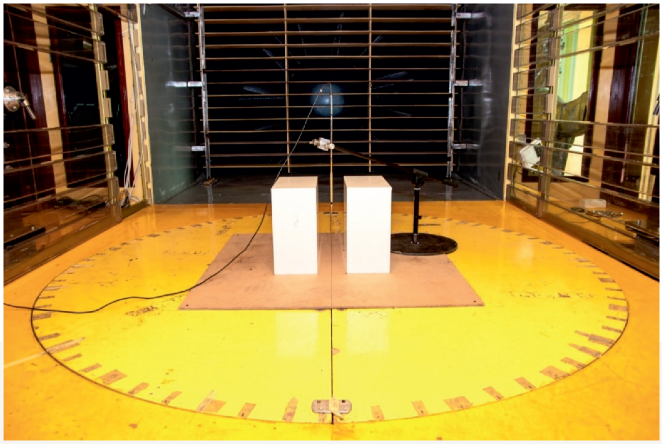


Fig. 7. Solid 4 during wind tunnel tests with the measurement system

3. Results of the measurements

The results obtained from the wind tunnel tests are presented in Fig. 8–4.5.

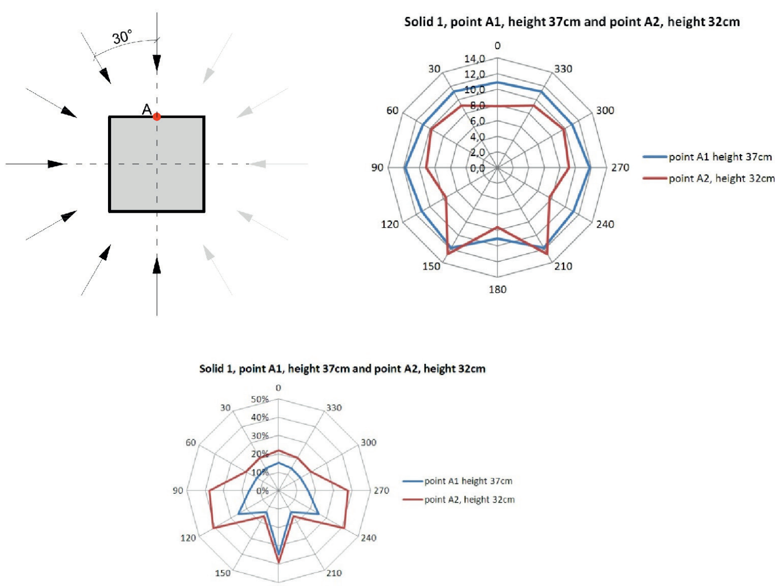


Fig. 8. Directions of inflowing air for Solid 1 (a), a comparison of average wind speed for point A1 – 37 cm height (blue) and A2 – 32 cm height (red) (b) and the turbulence (c)

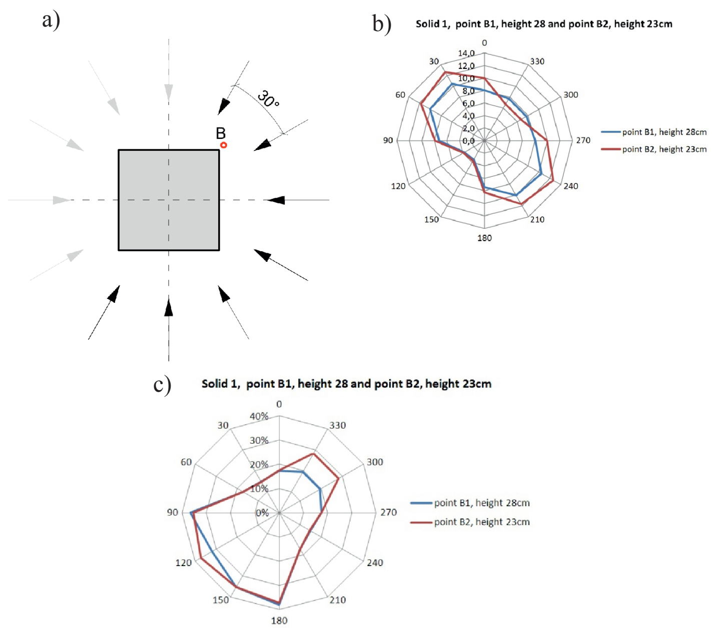


Fig. 9. Directions of inflowing air for Solid 1 (a), a comparison of average wind speed for point B1 – 28 cm height (blue) and B2 – 23 cm height (red) (b) and the turbulence (c)

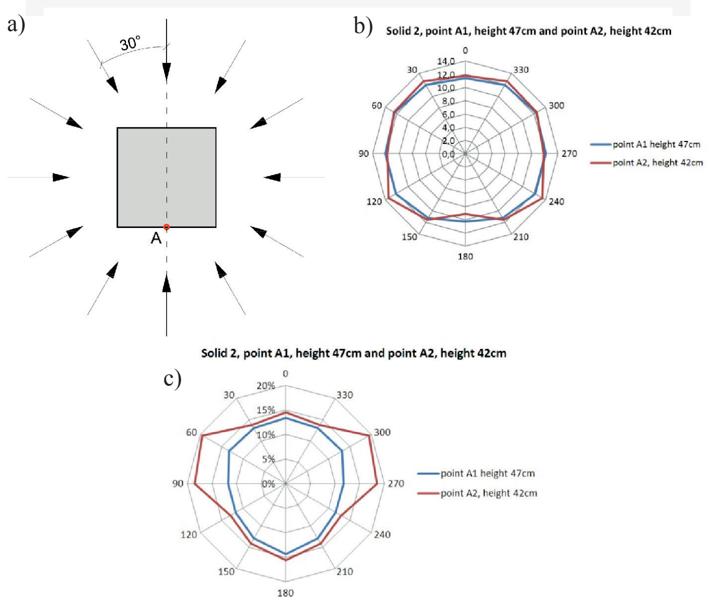


Fig. 10. Directions of inflowing air for Solid 2 (a), a comparison of average wind speed for point |A1 – 47 cm height (blue) and A2 – 42 cm height (red) (b) and the turbulence (c)

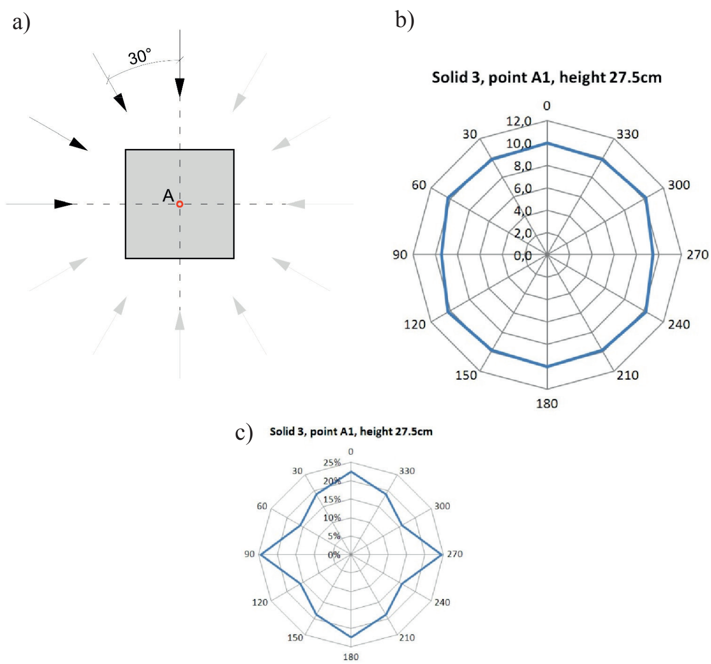


Fig. 11. Directions of inflowing air for Solid 3 (a), a comparison of average wind speed for point A1 – 27.5 cm height (b) and the turbulence (c)

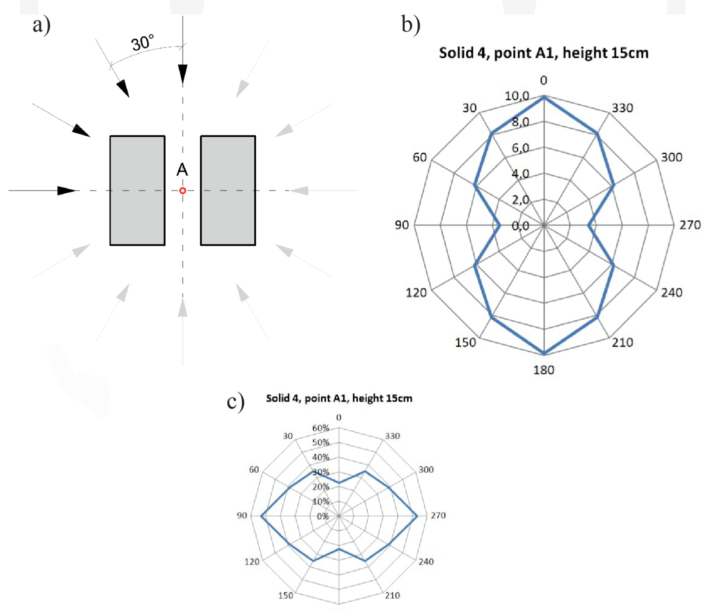


Fig. 12. Directions of inflowing air for Solid 4 (a), a comparison of average wind speed for point A1 – 15 cm height (b) and the turbulence (c)

4. Analysis of the test results

Solid 1

Point A has a relatively regular distribution of wind velocity field for all directions of inflowing wind. The average wind speed at point A1 positioned above the point A2 is higher. It is also less differentiated for particular directions. The average wind speed for point A1 is 11m/s.

Wind speed diagram for point B shows a very high variation depending on the wind direction. Furthermore, the average wind speed is higher for point B2 located below the point B1. The maximum speed of inflowing air for point B2 was obtained for 30°, 60°, 210° and 240° directions, and remained at 11.5–12.5 m/s level. The minimum speed was recorded for 120°, 150°, 300° and 330° angles and remained at 4–7 m/s level.

Relatively regular distribution of wind velocity (high homogeneity) as well as a high value of wind speed gives point A an advantage in comparison with point B. Point A1 is therefore the best point for the location of a small wind turbine for buildings of shape similar to solid 1.

Solid 2

Wind speed diagrams for Solid 2 shows a very high homogeneity for different wind directions. Moreover, differences between point A1 and A2 are slight. For every direction, the wind speed reaches value of 12 m/s. The only exception is for 180° angle of inflowing air where the speed drops to 10 m/s. Both points A1 and A2 have very favourable conditions for placing small wind turbines for buildings of shape similar to solid 2. It gives great opportunities for designers.

Solid 3

Wind speed diagrams for Solid 3 show a very high homogeneity for different wind directions. Wind speed reaches value of 10 m/s. Point A1 has favourable conditions for wind turbine placement. The results obtained during this study case shows that there was no increase of wind speed in the gap between segments of the building. The results of this study case show that placement wind turbine in the gap between the segments of building is not better than positioning it on the roof of that building.

Solid 4

The point A1 is located between two buildings. For angles between 45–135° and 225–315°, a strong slipstream effect (commonly identified with obstructing) was observed. The maximum speed of inflowing air was obtained for 0° and 180° angle. It reached almost 10m/s. Minimum wind speeds was obtained for 90° and 270° angle. It reached 3.5 m/s. In addition for these angles turbulence strongly increased – from 17% to 50%. It is a negative phenomenon for wind turbines. Taking into consideration narrow range of angles in which point A1 is exposed to inflowing air a location of wind turbines that can be used effectively is highly limited.

6. Conclusions and recommendations

The results of this study are very interesting. A comparison between the cases allowed for making the following conclusions.

– Point A1 for Solid 1 and points A1 and A2 for Solid 2 are particularly the most attractive due to wind conditions. A high homogeneity of the average wind speed justify locating wind turbines in these points.
– Point A1 for Solid 3 has worse exposure values due to wind. Nevertheless, it should not be omitted, since it is an interesting architectural solution. Point A1 for Solid 4 may have economic justification for only those places with high predominance of wind inflowing from one direction [2, 3, 6, 7].

Two important factors should be highlighted:

Tested models of box-shape buildings have sharp edges. In such cases, influence of Reynolds number is not significant and can be neglected. Therefore, the ratios of average wind speed at the measuring points $\overline{v}_i$ to average wind speed $\overline{v}(z_{ref})$ for tested models and full scale buildings are practically the same in a wide range of wind speed.

Vertical profile of the mean wind speed shows an obvious relation worth consideration. The higher wind turbines are placed along a facade or on the roof of a building, the higher average wind speed they are exposed to. It should response with greater amount of energy received from wind [6, 3].

References

[1] Abohela I., Hamza N., Dudek S., *Effect of roof shape on energy yield and positioning of roof mounted wind turbines*, Proceedings of Building Simulation 2011.

[2] Bukala J., Damaziak K., Kroszczynski K., Krzeszowiec M., Malachowski J., *Investigation of parameters in fluencing the efficiency of small wind turbines*, Journal of Wind Engineering and Industrial Aerodynamics 146, 2015, 29–38.

[3] Bukala J., Damaziak K., Karimi H., Kroszczynski K., Krzeszowiec M., Malachowski J., *Modern small wind turbine design solutions comparison in terms of estimated cost to energy output ratio*, Renewable Energy 83, 2015, 1166-1173.

[4] Cochran B.C., Damiani R.R., *Integrating Wind Energy into the Design of Tall Buildings – A Case Study of the Houston Discovery Tower*, WINDPOWER 2008.

[5] Flaga A., *Wind engineering – fundamentals and applications*, Arkady, Warsaw, Poland, 2008 (in Polish).

[6] Flaga A., *Wind power plants*, Wydawnictwo Politechniki Krakowskiej, Kraków 2012 (in Polish).

[7] Grieser B., Sunak Y., Madlener R., *Economics of small wind turbines in urban settings An empirical investigation for Germany*, Renewable Energy 78, 2015, 334–350.

[8] Ledo L.; Kosasih P.B.; Cooper P., *Roof mounting site analysis for micro-wind turbines. Renew*, Energy 2011, 36, 1379–1391.

[9] PN-EN 1991-1-4 Eurocode 1: Actions on structures – Part 1-4: General actions. Wind actions.