EXPERIMENTAL INVESTIGATION OF WIND FLOW AROUND LOW-RISE TILTED HOUSE

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Summary: *An experimental investigation has been conducted in order to give insight into wind flow characteristics in urban areas, in particular, its effects on low-rise buildings. Analyses are based on the results from atmospheric boundary layer wind tunnel experiments. Building model is a 1/75th scale model of a low-rise tilted house with roof inclination of 45°. Aiming to introduce the effects of neighbouring buildings, a comparative study of two configurations is presented, one with isolated principle building and another with four similar buildings surrounding the principle one. Additionally, the influence of the wind approaching angle is considered through the analyses of three directions: 0°, 45° and 90°. Wind velocity profiles above the roof of the principal building and pressure distribution on its surface are analysed in the paper.*

Keywords: *Wind Tunnel, Low-rise building, Interference Effects, Surface Pressure Distribution*

1. INTRODUCTION

World population is increasing every day. From 1.5 billion in 1900 to 6.1 billion in 2000 [1], today there are around 7.68 billion of us on earth [2]. Such an increase is followed by higher energy demand. The reduction in exploitable sources, huge environmental pollution and high price are some of the most reported problems of the traditional energy resources. As the result of seeking for the new one, the renewable energy resources have been ascertained as an appropriate alternative to traditional fossil fuel energy generation, among which wind energy has demonstrated outstanding characteristics and has attracted the world's attention. It has been defined as "the world's fastest-growing renewable energy source" with 30% growth annually on average throughout the last two decades [3]. New trends are changing the way energy is made and used. Lots of people are making their own energy at home using wind and solar as they are the most feasible

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renewable energy sources. Beside advantages due to producing energy at the place of its consumption, the impact on the Earth's natural environment is significant through the reduction of the carbon footprint. The mounting site for any turbine on a building should be assessed so that the optimum annual amount of energy can be obtained. To achieve it, detailed analysis of different factors should be involved, such as the direction of the mean wind speed, the interaction of the building envelope with the wind flow and the level of turbulence the turbine is exposed to.

Due to the large roughness length, the urban environment is characterized by low wind speed and high turbulence intensities compared to the rural areas. These high levels of turbulence intensity are affecting the operability and the lifetime of wind turbines [4].

Many researchers have been attracted with issues of wind harvesting in urban areas and deal with them using wind tunnel experiments [5], [6] and computational techniques [7], [4] and [8]. Wind tunnel experiments in [5] demonstrate that the wind flow and turbulence intensities at the roof level are strongly dependant on the roof shape but less on the areal building density. In [6] the results show that there is a significant influence of the upstream building on the wind characteristics above the principal one. Mounting height, the wind speed and the probability distribution of the wind speed above the flat roof have been analysed in [7]. Numerical studies in [4] give the above roof wind flow characteristics in three suburban landscapes characterized by houses with different roof profiles. The investigation of the location-specific attractiveness of small wind turbines (SWT) for private households has been conducted in [8], in order to assess the economic viability of an investment in SWT. It shows that the location of SWT in the urban area is crucial for their economic feasibility.

In the present work, local wind flow characteristics above the house with a tilted roof exposed to wind flow in urban areas are presented in the light of wind harvesting potential, regarding the experimental results. This paper is organized into four sections. Section 2 refers to the experimental setup and describes the wind tunnel facility, model of the building and analysed configurations, as well as the instrumentation used for velocity and pressure measurements. In section 3, the main flow features above the roof of the building are described and the effect of the neighbouring buildings in different configurations. The paper ends with conclusions in Section 4.

2. EXPERIMENTAL SETUP

The presented investigation includes the outcome of the atmospheric boundary layer wind tunnel experiments on urban wind harvesting around low-rise tilted roof house. Tests were carried out on a 1:75th scale model. Experiments were conducted in the ABL wind-tunnel of the Ruhr-University Bochum, Germany, within a Short Term Scientific Mission of the COST Action TU1304. Wind tunnel has a rectangular cross-section, with weight, height and length of the test section 1.8m, 1.6m and 9.4m, respectively. The approaching flow represents an urban wind exposure using the spire-roughness technique.

The characteristics of the incoming flow field were measured at the distance of 1m in front of the principal building. Established mean wind profile matches one of the power low with the exponent 0.2. Measurements of mean stream-wise wind velocity (U) and turbulence intensities in stream-wise (I_U) and vertical (I_W) directions are presented in

Figure 1a. Figure 1b shows a stream-wise velocity spectrum at the height of the model – reference height (z_{ref}=20cm). Mean stream-wise wind speed (U_{ref}) at the referent height (z_{ref}) is 13.8m/s and this value has been used to normalize the velocity profile for all measurements. Turbulence intensities in stream-wise and vertical directions are 16% and 13%, respectively at z_{ref}.

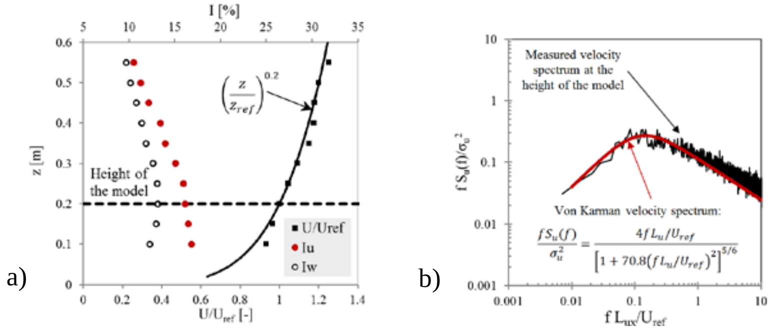

Figure 1. Wind flow characteristics in wind tunnel: a) mean stream-wise wind speed (U/U_{ref}) and turbulence intensities in stream-wise (I_U) and vertical (I_W) direction (coordinate z=0 is related to the floor of the wind tunnel); b) stream-wise velocity spectrum at the height of the model

Building under the investigation is a tilted house with roof inclination of 45°. The model dimensions, length (L), width (B) and height (H), are shown in Figure 2a. Two different configurations have been considered. The first one (C1) has only isolated principle building Figure 2d, and the second configuration (C2) has the additional four interfering buildings, surrounding the principle one Figure 2b,e. All buildings (principle and interfering ones) are of the same geometric characteristics. Three different approaching wind angles have been considered for configuration C1, 0°, 45° and 90° and two for configuration C2, 0° and 45°. Experiments were performed with a Reynolds number of $1.8*10^5$, which is defined based on the building width (B=100mm) and referent velocity (U_{ref}=13.8m/s). Blockage ratio for the worst case (configuration C2, wind angle of 45°) is 4.7%.

Velocity components were measured with two-dimensional hot wire anemometer (HWA). It was located above the roof of the principal building. Measuring points were non-uniformly distributed at five heights (from 5cm to 40cm) above two points on the ridge. Points on the ridge are marked with the Roman numbers (I) and (II) and their exact position on the roof is given in Figure 2c,f. In order to create as less as a possible disturbance in the flow field, only one HWA was used for all tests. Measurements for each point were performed separately. Two components of the velocity vector were covered, streamwise and vertical. The sampling frequency of 2000Hz was applied.

Surface pressure measurements were carried out in 70 points on the roof of the principal building, and 20 points on the ring on its sides. The scheme of the pressure taps is given in Figure 2c,f. Measurements were conducted simultaneously in all points, using a multi-channel simultaneous scanning measurement system with the sampling frequency of 1000Hz.

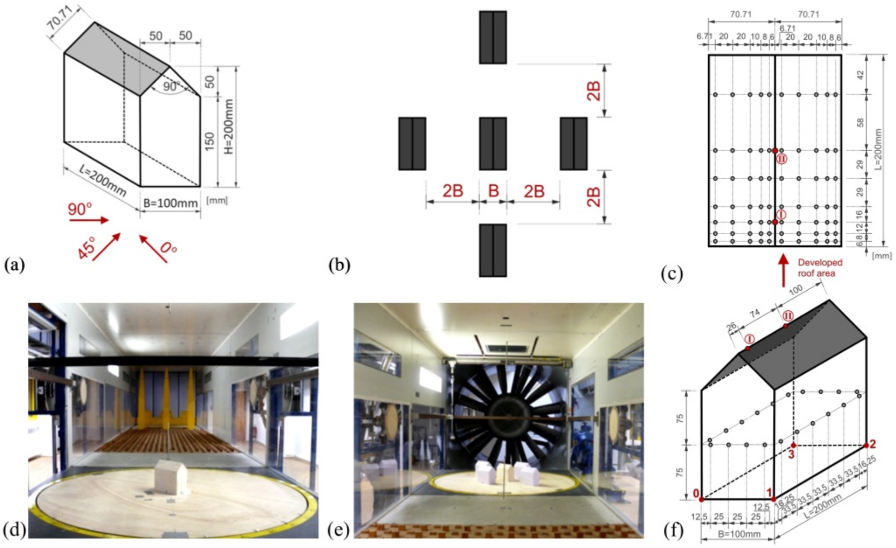

Figure 2. (a) Dimensions of the tilted house model, (b) arrangement of the houses according to the interference configuration, (c) and (f) positions of the pressure and velocity (circled values on the roof) measurement points on the model (d) tilted roof model mounted on the rotating table in the wind tunnel, (e) the principle house surrounded by the interference houses mounted in the wind tunnel

3. EXPERIMENTAL RESULTS

The main goal of this section is to give the insight in the velocity profile above the roof of the principal building for two configurations (C1 and C2), considering three different wind angles (0°, 45° and 90°). It is divided into four subsections which analyse flow pattern, turbulence intensities, skew angles, flow acceleration and interference effect.

Flow patterns

Figure 3 presents these profiles by means of stream-wise and vertical components of velocity vectors and turbulence intensities. Values of the velocity vector components are normalised using the reference velocity U_{ref}. As a relevant parameter for the analysis, the increase of the stream-wise wind speed has been obtained using relation $(U-U_{ref})/U_{ref}$ and expressed in percentages in Figure 3. Turbulence intensities in stream-wise (I_U) and vertical (I_W) directions were calculated using the following expressions:

$$I_U = \sigma_U / U \ , \ I_W = \sigma_W / U \qquad (1), (2)$$

Where σ_U and σ_W are standard deviations of stream-wise and vertical components of velocity vectors, and U is the mean stream-wise wind speed.

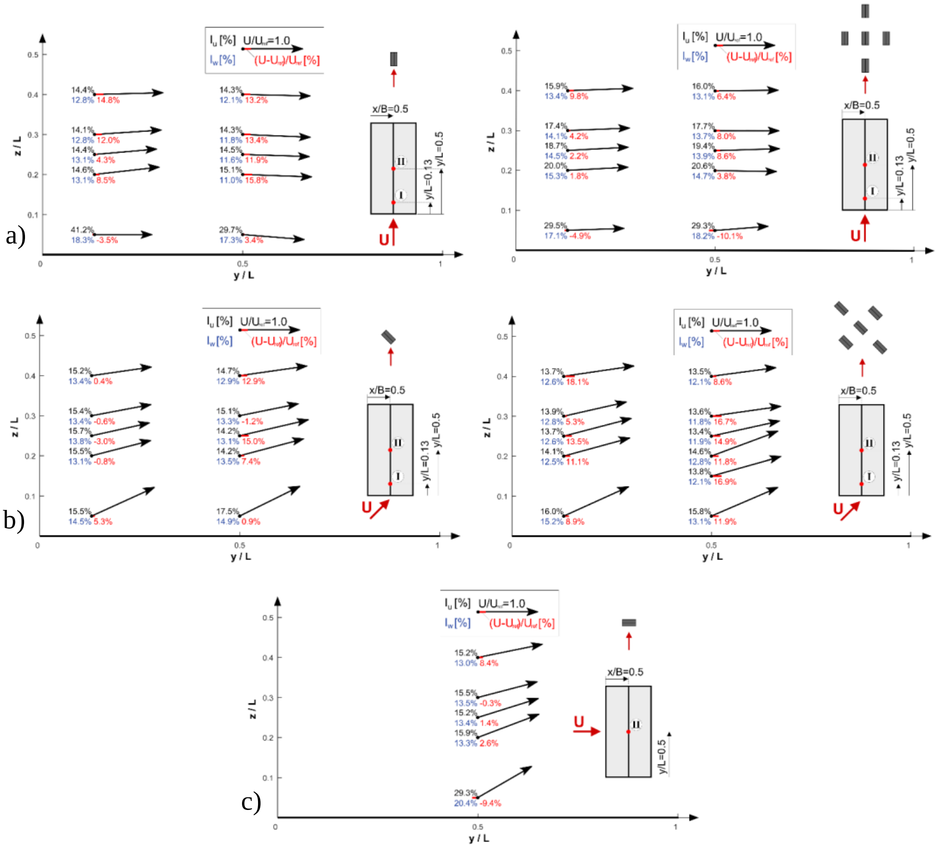

Figure 3. Profiles of velocity vectors based on stream-wise and vertical velocity component, stream-wise turbulence intensity I_U, vertical turbulence intensity I_W and percentage increase in the stream-wise wind speed for wind angle of a) 0°, b) 45°,c) 90°

Looking at the Figure 3a, for wind angle of 0°, in configuration C1 velocity profile above point (I) indicates a separation bubble, developed at the upstream edge. This is confirmed by high values of turbulence intensities in the vicinity of the roof along the ridge. It can also be observed that the velocity vector above point (II) at z/L=0.05 is pointing downwards which suggests that the flow tends to attach to the roof. Velocity vectors above that height are nearly parallel to the ridge which can be a hint to derive the height of the separation region. One indicator for such a bound is the wind speed at z/L=0.2 which is 15.8% larger than the reference one (U_{ref}) and decreases to 11.9% at z/L=0.25. This is also verified by the turbulence intensities in these points which are comparable to the corresponding reference unobstructed stream values. For configuration C2, results pronounce a flow pattern without the indication of the separation region; velocity vectors are nearly parallel to the ridge. Nevertheless, an increase in turbulence intensities in the vicinity of the ridge, reaching up to a value of 30%, is typical for separation zone since it possibly indicates reverse flow region. Here, the accuracy of the measuring apertures should be taken into account [9]. Therefore, the results of velocity components in such an area cannot be treated as reliable.

In the case of 45° wind angle, Figure 3b, in both configurations (C1 and C2), velocity profiles point out a strong separation on the leeward side of the roof. The measured velocity vectors are pointing upwards with a larger gradient in the vicinity of the rooftop. Even strongly pronounced separation is occurred in the case of 90° wind angle in Figure 3c on the leeward side of the roof.

For a more detailed look at the flow pattern above the roof, surface pressure analyses have been done. Contours of the mean surface pressure coefficients for both configurations (C1 and C2), taking into account three different wind angles, are presented in *Figure 4*. The pressure coefficient, C_p is calculated using the following expression:

$$C_p = (p - p_0) / (0.5 \rho U_{ref}^{2}) \tag{3}$$

Where with p_0, ρ and U_{ref} are denoted unobstructed stream pressure, air density and the reference velocity, respectively.

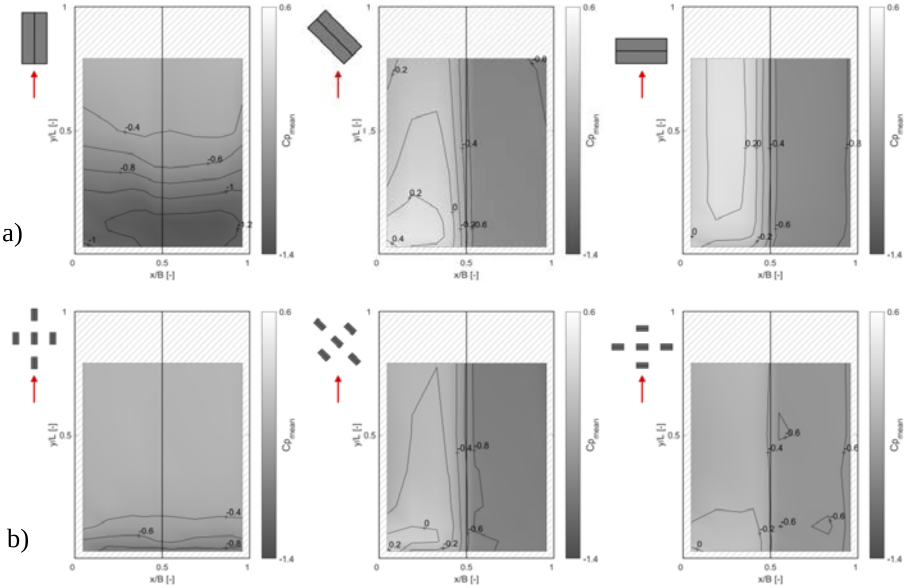

Figure 4. Contours of $C_{p,mean}$ on the roof of the principal high-rise building for different approaching flow angles and configurations a) C1, b) C2

For 0° wind angle, in C1 configuration, the reduction of the surface pressure occurs close to the upstream edge, followed by a growth of the pressure downstream. It suggests a large separation bubble close to the windward edge. The plot in Figure 5 for line x/B=0.45 parallel to the ridge shows characteristic upstream hump shape which is typical for the separation region followed by reattachment [10]. This shape is related to the high negative pressure values in the separation region. The largest suction was found directly below the average moving vortex core [11]. Length of the mean recirculation region is related to the peak location of the standard deviation value considering that the peak occurs just upstream of the mean reattachment position [10]. By contrast, in configuration C2 hump shape is lost, but large negative values on the upstream edge suggest a separation, which is confirmed by high turbulence intensities in Fa. In addition, a noticeable drop in values of $C_{p,mean}$ occur in the group arrangement as a result of the upstream building shading effect on the flow around the principle one. It is expected that the pressure field shows symmetry for left and right side of the roof in both configurations, but slight variations exist due to the non-symmetric distribution of the pressure taps as shown in Figure 2c.

In contrast to 0° cases, pressure coefficient distributions for 45° and 90° wind angles show patterns that indicate flow separations on the leeward side of the roof.

For C1 and C2 configurations with the attack wind angle of 45° similar surface pressure coefficient distribution can be observed.

In the case of 90° wind angle, in both configurations, the windward side of the roof is under pressure while the leeward side is in suction. In the group configuration, small variations of pressure coefficients can be noticed in *Figure 4*b. The reason may be found in the arrangement of the neighbouring buildings. The upstream building is shading a principle one as it was also observed in group arrangement for 0° wind angle.

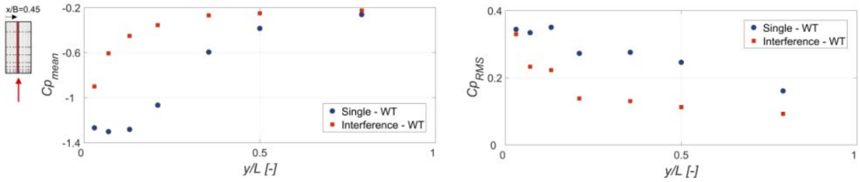

Figure 5. Mean and standard deviation distribution of pressure coefficient along the roof line x/B=0.45 for 0° wind angle

Turbulence intensities

An important criterion when considering the best configuration for wind harvesting depending on the arrangement and approaching wind angle is the level of turbulence intensities. Recommendations from [12], suggests that wind turbine in urban areas should not be exposed to the wind with a turbulence intensity greater than 16-18% since it affects its operability and lifetime. Analysing the experimental results presented in Figure 3 certain conclusions can be reached.

For 0° wind angle, in configuration C1 values comparable to the reference unobstructed stream values at an appropriate height can be noticed. Only exceptions are measurements at height z/L=0.05, where turbulence intensities in the stream-wise direction above point (I) reaches 41.2%, and above point (II) 29.7%. These high values suggest a separation in this area. Similar separation was observed for group arrangement where I_U reaches up to 30% in the vicinity of the ridge. Measured values above the roof for z/L=0.2 - 0.3 are in the range 17-20% for I_U and 13.7-15.3% for I_W. For the height of z/L=0.4 and higher, turbulence intensities are comparable to reference values of 16% and 13% for stream-wise and vertical directions, respectively.

In case of 45° wind angle, for both configurations, all values of turbulence intensities do not exceed 16% for I_U and 15% for I_W, except for the point (I) at z/L=0.05 in C1 configuration, where it was measured 17.5% in stream-wise direction.

For 90° wind angle, these values are similar to the previous case except in point close to the ridge where high turbulence level of 30% in stream-wise and 20% in a vertical direction can be noticed.

Flow acceleration and inclination of the velocity vectors

Focusing on the angle of attack of 0° in Figure 3a and configuration C1, an increase of 15.8% above point (II), at height z/L=0.2 can be observed. As previously mentioned, this can indicate the upper bond of the separation region. Measurements in the first point above shows a slight decrease in wind speed, after which flow speed starts to increase with height, and reaches the value of 13.4% at z/L=0.3. Flow above point (I) is not strongly affected by the separation region. That is confirmed by the smaller values of the wind speed at z/L=0.2. The most significant acceleration of 14.8% has been achieved at height z/L=0.3. In a group arrangement, acceleration is less pronounced than in an isolated building case. The maximum value of 9.8% is reached at height z/L=0.4, above point (I).

When considering the angle of attack 45°, Figure 3b shows measurements that are considerably different from those obtained for 0° wind angle. The maximum acceleration of 16.9% has been measured in group arrangement at z/L=0.2. Also, significantly larger inclinations of the velocity vectors are recorded compared to configuration C1, while for points above z/L=0.2, they are around 28% in both configurations.

In the case of 90° wind angle, Figure 3c, acceleration occurs only above the height of z/L=0.4, reaching up to a value of 8.4%. Inclinations of the velocity vectors are even higher than those obtained for 45° wind angle.

Interference effect

Looking at the turbulence intensity level above the roof of the principal building, in case of 0° wind angle, C2 configuration, only above the height of z/D=0.4 its level becomes comparable to the corresponding unobstructed stream level. This negligible effect is caused by the upstream building position. Namely, upstream building generates a shear flow which affects the downstream principle one, similar is observed in [6]. Its influence is limited to the height of about the same as building width.

Opposite to the 0° case, for 45° wind angle in a group arrangement, a slight decrease in turbulence intensities above the roof has been measured compared to isolated building case. They are even lower than reference unobstructed stream values for points higher than z/L=0.2. Even in the zone close to the ridge, these values are comparable to the reference. The flow acceleration above the roof of up to 16.9% in the stream-wise direction in group arrangement can be a consequence of the position of the surrounding buildings. Namely, for the attack wind angle of 45°, the upstream buildings do not overshadow the principal one as for 0° wind angle case, since they have a projected distance of $D=2\sqrt{2}B$ in the plane normal to the attack angle. Here, the Venturi effect can be detected due to the narrowed space when winds funnel between two upstream buildings, further enhancing the acceleration of wind speed. Analysing the turbulence intensities for 45° wind angle, a slight decrease in group arrangement can be noticed, compared to single building case. This may lead to the conclusion that the shear flow which is generated from the upstream buildings in group arrangement does not affect the principle building downstream.

4. CONCLUSION

Summing up all the results, the importance of the approaching wind angel may be noticed, as well as the configuration type and the arrangement of the surrounding buildings. According to different criteria, certain conclusions can be made for further analysis of the selection and placement of a wind turbine on the rooftop of the house:

- Looking at the turbulence intensities, the most favourable combination would be group configuration with a 45° wind angle. Nevertheless, each case meets the requirements from the [12] above the height z/L=0.2, except the C2 configuration for 0° angle of attack in which they are satisfied above the height z/L=0.4;
- Regarding the wind acceleration, the best option for wind harvesting is the case of a group arrangement with 45° wind angle. The second choice would be the case of a single building exposed to the wind with the attack angle of 0°.

Considering the potentials for wind harvesting, group arrangement with 45° wind angle fits the best in the requirements framework. If the case of the isolated building is analysed, the best results have been obtained for the approaching wind angle of 0°.

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EKSPERIMENTALNO ISPITIVANJE TOKA VETRA OKO NISKE DVOVODNE KUĆE

Резиме: *Eksperimentalno ispitivanje je sprovedeno sa ciljem da se dobije uvid u karakteristike strujanja vetra u urbanim sredinama, posebno uticaj na niske objekte. Istraživanje se zasniva na rezultatima eksperimenata iz aerotunela u atmosferskom graničnom sloju. Model zgrade je niska dvovodna kuća u razmeri 1:75 sa nagibom krova od 45°. Sa ciljem da se uključi uticaj susednih objekata, predstavljena je uporedna analiza dve konfiguracije, jedne sa izolovanim posmatranim objektom i druge sa četiri slična objekta koja okružuju posmatrani objekat. Dodatno je razmatran i uticaj ugla pod kojim vetar deluje kroz analizu tri pravca: 0°, 45° i 90°. U radu su prikazani profili brzina vetra iznad krova posmatranog objekta i raspodela pritisaka na njegovoj površini.*

Кључне речи: *Aerotunel, niska zgrada, uticaj okruženja, raspodela površinskog pritiska*