EXPERIMENTAL STUDY OF AERODYNAMIC CHARACTERISTICS AND EVALUATION OF WIND FLOW CONCENTRATOR EFFICIENCY

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ АЕРОДИНАМІЧНИХ ХАРАКТЕРИСТИК ТА ОЦІНКА ЕФЕКТИВНОСТІ КОНЦЕНТРАТОРА ВІТРОВИХ ПОТОКІВ

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ABSTRACT

An experimental study of the wind flow concentrator of a new design using the wind tunnel of subsonic speeds was carried out. Experimental studies in the wind tunnel were performed at an air flow velocity of 1 m/s. The fields of velocity and pressure distribution in the areas in front of the wind flow concentrator and in its central part are obtained. Based on the obtained data in the Mathcad, contour graphs are constructed, which show the distribution of wind flow velocities and pressures in the investigated part of the wind flow concentrator. As a result, it was obtained that in the area of the wind turbine blades there is an increase in the velocity of air masses by 4 times compared to the air velocity at the entrance to the wind flow concentrator. The proposed design of the wind flow concentrator makes it possible to increase the efficiency of the wind turbine and receive electric energy at low wind speeds, when the bladed wind turbines do not generate electricity. Verification of experimental data with data of numerical modeling of hydrodynamics in the wind flow concentrator is carried out. The evaluation of the use of wind flow concentrator to increase the efficiency of wind turbines with a vertical axis of rotation is carried out.

РЕЗЮМЕ

Проведено експериментальне дослідження концентратора вітрових потоків нової конструкції з використанням аеродинамічної труби до звукових швидкостей. Експериментальні дослідження в аеродинамічній трубі проводилися при швидкості повітряного потоку 1 м/с. Отримано поля розподілу швидкостей і тисків на ділянках перед концентратором вітрових потоків та в центральній його частині. На основі отриманих даних в середовищі MathCAD побудовано контурні графіки, які показують розподіл швидкостей та тисків вітрового потоку в досліджуваній частині концентратора вітрових потоків. В результаті отримано, що в зоні знаходження лопатей вітротурбіни має місце збільшення швидкості руху повітряних мас в 4 рази в порівнянні з швидкістю руху повітря на вході в концентратор вітрових потоків. Запропонована конструкція концентратора вітрових потоків дає можливість підвищити ефективність вітротурбіни і отримувати електричну енергію при малих швидкостях вітру, коли лопатеві вітротурбіни не генерують електричну енергію. Проведено верифікацію експериментальних даних з даними чисельного моделювання гідродинаміки в концентраторі вітрових потоків. Проведена оцінка використання концентатора вітрових потоків для підвищення ефективності вітрогенераторів з вертикальною віссю обертання.

INTRODUCTION

The efficiency of modern blade type wind turbines (WT) has approached the maximum values of generated power. In contrast to blade type wind turbines, vertical-axis wind turbines can have much higher theoretical values of the wind flow energy utilization factor. Therefore, the development of new designs of vertical-axis wind turbines (VAWT) is of perspective. In this regard, in the field of small and medium capacities, it is advisable to use vertical-axis, orthogonal wind turbines. There are number of theoretical works in which the prospects of development of new designs of vertical axis wind turbines are shown (*Colin Walsh, 2019*).

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In recent years, researchers have conducted in-depth studies of the aerodynamic characteristics of vertical-axis wind turbines in different conditions, including their use in terms of urban development (*Balduzzi F. et al., 2012*). Various methods were used to study the conditions of wind flow around the vertical-axis wind turbines, including an analytical model based on the method of double multiple flow pipes, to calculate the characteristics of the rotor for vertical-axis wind turbines with straight variable pitch blades (*Soraghan C.E, et al., 2013*), the method of discrete-vortex modeling (*Wang L. and Yeung R.W., 2016*), cascade model (*Mandal A. and Burton J., 1994*) and 2D and 3D flow modeling around the turbine (CFD modeling) (*Franchina N. et al., 2019*). Among these methods, CFD modeling is considered as a method of high accuracy, which can give a detailed picture of the field of velocities and pressures in the air flow (*Rezaeiha A. et al., 2017*), and also make it possible to detect the interaction of the oncoming flow with the blades and to obtain the existing dynamic effects in the studied wind generation systems (*Ghasemian M. et al., 2017*). An important role in the study of the conditions of hydrodynamic flow when flowing around the vertical-axis wind turbine is played by studies in the wind tunnel, which allows to obtain local characteristics of the flow and to suggest methods to increase their efficiency (*Battisti L. et al., 2018*). All these methods were used to evaluate the influence of various geometric parameters, including the function of the optimal pitch of the blades, based on the optimal angles of the blades (*Xu Y.L. et al., 2019*), symmetrical and curved blades (*Bausas M.D. and Danao L.A.M., 2015*), the influence of strength and aerodynamic profile of the blades on the characteristics of vertical-axis wind turbines (*Subramanian A. et al., 2017*) and the effect of rotor elongation on power characteristics in three-dimensional analysis using the panel method (*Li Q. et al., 2017*).

The aerodynamic parameters of the hybrid-shaped vertical-axis wind turbine in different operating conditions were also studied, which include different speed coefficients of the blade tip (tip speed ratios), torque factor, power factor, (*Ashwindran S. et al., 2019*), Reynolds numbers (*Hand B. et al., 2017*), turbulence intensity (*Su J. et al., 2*019), and also instability of a wind flow (*Danao L.A. et al., 2013*). In addition to the above studies, some new configurations of vertical-axis wind turbine and blade profiles have recently been suggested. *Xu Z. et al. (2018)* conducted an experimental and numerical study on a series of new disk wind rotors used in a small-scale wind turbine. The influence of the blade velocity coefficient, inclination angle and opening angle is estimated and a higher wind rotor power factor is obtained.

Perez-Torro R. and Kim J.W. (2017) investigated the flow characteristics of the NACA0021 wing with sinusoidal corrugated blades using the large vortex simulation technique (LVS). The results showed that the increased lifting force and the reduced traction force are achieved by using the wavy front of the blade instead of the straight front of the blade. Subsequently, *Wang Z. and Zhuang M. (2017)*, studied the conditions for improving the energy performance of the traditional model of H-type vertical-axis wind turbine by using sinusoidal teeth on the leading edge of the turbine blades to control the dynamic flow distribution at low blades` speed coefficient. The output power results showed that the improved configuration has reduced the impact of the dynamic delay effect and increased the generator torque. *Arpino F. et al., (2018*), suggested a new vertical-axis wind turbines, which use a Darier rotor with three pairs of blades, each of which consists of a main and auxiliary wing. It is proved that the new configuration has a higher power factor at a lower speed coefficient of the tip compared to the classic straight blade of vertical-axis wind turbine, which is the most adaptive for use in urban development. *Chong W.T. et al., (2017),* suggested a wind turbine with transverse blades, consisting of three vertical blades and six horizontal blades, located in the direction of the transverse axis.

In addition to improving the power factor of the wind turbine, a number of authors have suggested the use of auxiliary devices to increase the energy of wind flow, in particular deflectors (*Takao M. et al., 2009; Wong K.H. et al., 2018*) and diffusers (*Zanforlin S. and Letizia S., 2015*). Watanabe and others (*Watanabe K. et al., 2016*) used the structure of the diffuser in the directing channels, utilized in the wind turbine, to increase its power factor. In their research, they also optimized the geometry of this diffuser.

Another way to increase efficiency is to use a device for concentrating the wind flow with curved contours (*Yan Li, et al., 2019*), which are installed in the upper and lower part of the rotor, to increase the wind flow energy.

Installation of wind prefabricated device on the rotor is one of the most perspective researches in recent years, which makes it possible to increase the speed of self-starting of the rotor. *Ji J.F. et al., (2012)*, suggested one of the designs of wind turbine with wind shields, installed around the wind turbine along the inlet flow direction, which can control the inlet flow and increase the wind speed when the wind blows on the rotor. The results showed that the suggested designs to increase the wind speed improved starting and energy indicators of the wind turbine.

Huang J. et al., (2013), studied the design of wind turbines with directing blades, the directing blades of which were installed around the rotor along the inlet flow direction. Results of the study showed that the directing blades improved the starting performance of wind turbine. Similarly, *Xiaohang Wang et al. (2018),* introduced a patented V-shaped directing blade with a solar and wind energy generation system, mounted on an eco-roofing system. As a result of experimental studies, it was found that the speed of self-starting and the speed of rotation of the wind turbine installed over the roof with a V-shaped blade, were significantly increased compared to the wind turbine designs without this type of blade. *Wong Kok Hoe et al., (2018),* using laboratory tests and computer simulations investigated the aerodynamic effects of the flow conditions of the flat deflector and the velocity fields. This deflector was placed in the lower part in front of the micro-rotor of the wind turbine and used to increase the wind flow velocity. Analysis of the simulation results shows that the deflector increases the wind flow velocity in areas located near the wind turbine blades.

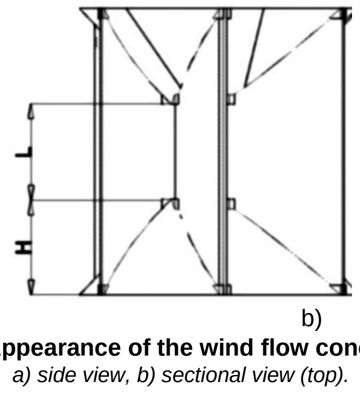
Li Yan et al., (2018), suggested an innovative device for the wind flow concentration that have a shortened conical shape, which is installed in the upper and lower part of the rotor. This type of location increases the velocity of the input flow and increases the efficiency of wind turbines.

The main idea of the study (*Abdul Latif Manganhar et al., 2019*) is to use special deflectors that increase the wind flows velocity of the wind power turbine. The suggested rotor design consists of four equidistant vertical walls, which are rotated at an angle of 45 degrees relative to the wind flow direction. The rotated wall deflects the wind flow directing it normally to the surface of the blade. The suggested design has two advantages over the known ones - it prevents the reduction of the negative impact of turbulent flows on the turbine blade and increases the torque.

Vergaerde A. et al., (2020), investigated the influence of the close location of two VAWT on the generated power in the wind tunnel. The increase in power depends on the distance between them, the speed coefficients of the blade tip and the direction of rotation of the two wind turbines. *Kim D. and Gharib M. (2013),* used a flat plate in front of a pair of vertical-axis wind turbines to test its effect on the produced capacity of wind turbines. The effect of accelerating wind flow around the deflector was later confirmed by measuring velocities by visualizing wind flow (*Kim D. and Gharib M., 2014*). *Jin X. et al., (2018),* studied the efficiency of VAWT with a deflector, installed in front of two wind turbines, using three-dimensional (3D) CFD simulations. Based on the obtained results wind generation system (*Yichen Jianga et al., 2020*) was developed. This system consists of two counter-rotating wind turbine rotors and a deflector, which is located between these rotors.

MATERIALS AND METHODS

Development of wind flow concentrator. One of the promising designs of the wind flow concentrator (WFC) is the shape of a truncated cone with directing channels, which is shown in Fig. 1. The suggested concentrator of wind flow consists of a system of narrowing channels of the confuser type (*Gorobets V.G. and Masiuk M.Yu., 2021*). The upper and lower part of these channels are closed by conical surfaces, which makes it possible to concentrate the wind flow towards the rotor.



a) b)

Fig. 1 - Appearance of the wind flow concentrator

a) side view, b) sectional view (top).

According to the equation of continuity of flow in an incompressible liquid (gas), the use of confuser-type narrowing channels increases the flow velocity and contributes to the energy concentration of the wind flow in the direction of the rotor. The geometry of the directing blades of the channels is chosen to direct the wind flow at the optimal angle of attack on the turbine blades.

The suggested design of the wind flow concentrator is universal and works regardless of the wind direction, which flows through the directing channels of the confuser type, where its speed increases due to the Venturi effect.

As a result of using this type of device, can be obtained a greater power of wind flow per unit of area for any wind direction, which increases the performance of the wind turbine. Given the fact that the electromagnetic moment and power of the wind turbine are proportional to the square and the cube of wind speed, respectively, the use of a wind flow concentrator will improve the aerodynamic characteristics of the VAWT.

Design of an experimental sample of wind flow concentrator

Experimental studies of wind flow concentrator are carried out in a wind tunnel, which has the following characteristics: the transverse dimensions of the working area 0.3×0.3 m, the range of changes in wind flow velocity in the working area from 0 to 18 m/s. Based on these characteristics an experimental sample of wind flow concentrator with the following parameters, which are given in Table 1 was developed and designed. The suggested design of the wind flow concentrator contains 6 channels, for which the area of the input and output cross-section of a separate channel is S1 and S2, respectively (Fig. 2).

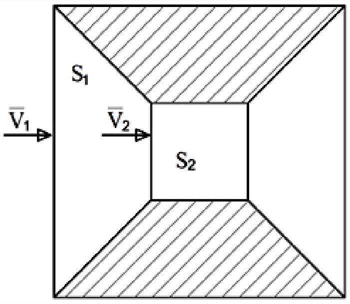


Fig. 2 – Transverse profile of the wind flow concentrator

a) b)

Fig. 3 – General view of the experimental sample

a) wind flow concentrator, b) working area of the wind tunnel with wind flow concentrator and turbine rotor.

Table 1

Structural parameters of the wind flow concentrator

Name	Dimensionality	Size
Cone height *H*	m	0.1
The height of the working area *L*	m	0.1
Blade thickness *l*	m	0.002
The size of the working area *LxR*	m	0.1x0.1
The area of the inlet of the channel S_1	m^2	0.0471
The area of the outlet of the channel S_2	m^2	0.0052

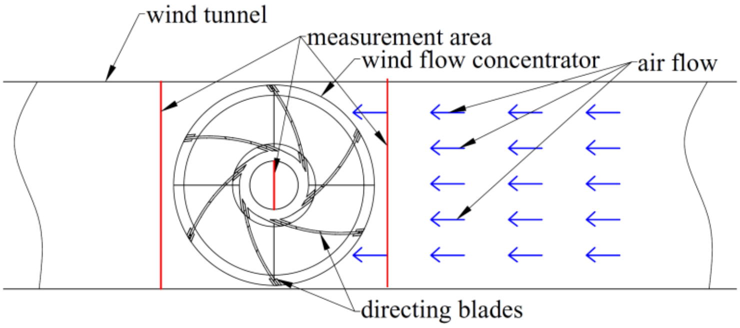
Research method. The general concept of the WFC is to increase the energy of the wind flow per unit area, increase the torque over the entire area of the blades, reduce the turbulence of the oncoming flow and stabilize the rotor rotation speed. The characteristics of the wind flow concentrator were found by modeling the aerodynamic flows using CFD modeling of commercial package ANSYS FLUENT for both a single channel and for the entire structure (*Gorobets V.G. et al., 2021*). The geometric shape of a single channel was selected from the conditions of minimum hydraulic losses during the passage of wind flow through each channel and the maximum value of the pressure force of this flow on the rotor blades. Experimental study of the vertical-axis wind turbine was conducted in the problem-scientific laboratory "Heat-mass transfer processes and alternative energy sources" at the Department of Heat and Power Engineering of the National University of Life and Environmental Sciences of Ukraine.

During the test, a 10-bladed H-rotor turbine with a rotor diameter of 0.1 m and a height of 0.1 m was used. The general view of the experimental sample of the wind flow concentrator and the turbine rotor is shown in Fig. 3.

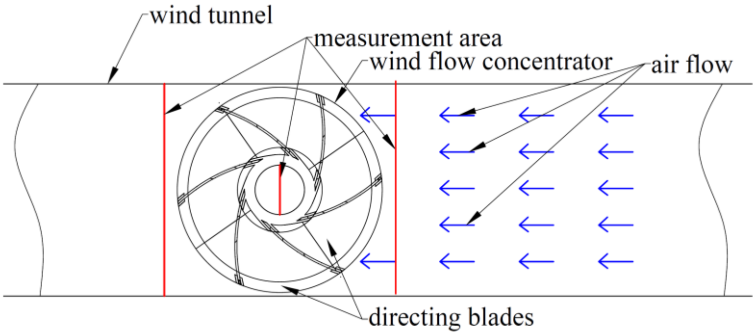
Given that the wind flow concentrator is not a symmetrical structure, before the study in the wind tunnel, an initial experiment was conducted for wind flow in its different directions. These studies make it possible to evaluate the efficiency of the wind flow concentrator in comparison with the known designs of vertical-axis wind turbines. The experiment was performed for two positions of the WFC relative to the wind flow direction (Fig. 4). For the first position, the flow direction coincided with the central axis of the inlet channel of the wind flow concentrator, and the accepted position of the concentrator corresponded to 0° (Fig. 4a). For the second position, the wind flow concentrator was shifted by 30°, at which the direction of wind flow was addressed to the edge of one of the walls of the directing channels (Fig. 4b).

During the experimental studies, the WFC was placed in the working area of the wind tunnel. Within the working section of the wind tunnel, a system of measurements of hydrodynamic values of wind flow was developed, namely the fields of velocities and pressures in the vertical section of the working area of the wind tunnel. The air velocity was measured with an AM-70 anemometer, and the pressure values were obtained using a Testo 510 differential manometer and a Pitot-Prantl tube. The measuring parts in the cross section of the working area of the wind tunnel were divided into 15 equal parts, in which measurements to obtain the fields of velocities and pressures in the air flow were made.

The measurement was performed directly in front of the wind flow concentrator and in its central part, where the rotor shaft with blades is located. The WFC was placed in the wind tunnel in accordance with the first position (Fig. 4a). The measurement areas were located directly in front of the wind flow concentrator and in its central part. (Fig. 4a).



a)



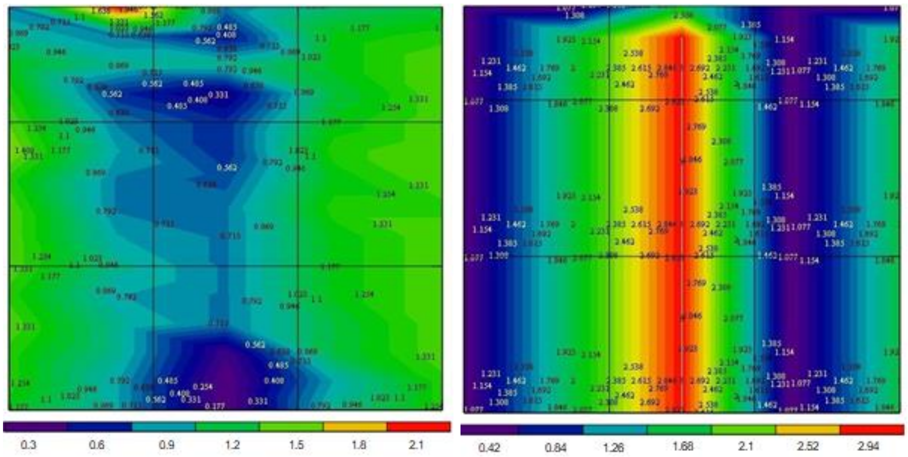
b)

Fig. 4 – Measurement areas for oncoming air flows in position
a) 0 ° to the wind flow concentrator; b) 30 ° to the wind flow concentrator.

RESULTS

Based on the obtained experimental data, contour graphs were constructed, which show the distribution of velocities and pressures in the wind flow in front of the wind flow concentrator (Fig. 5).

Analysis of the obtained graph of wind flow velocity distribution (Fig. 5a) shows that the air velocity increases near the side walls, while in the central part the velocity decreases due to the presence in the working area of the wind tunnel structure that creates aerodynamic resistance. The graph of pressure distribution (Fig. 5b) in the wind flow shows that the highest pressure values are observed in the central part of the vertical section of the wind tunnel, while the pressure drops near the side surfaces.



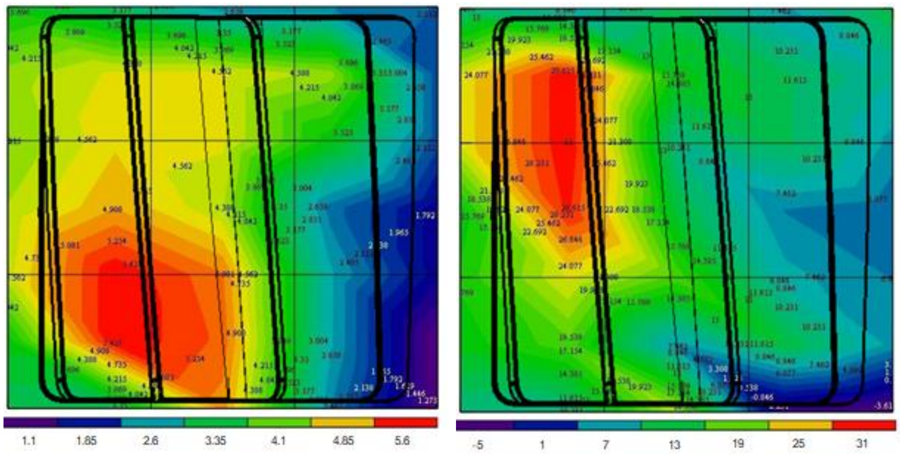
a) b)

Fig. 5 – Distribution of velocities (a) m/s and pressures (b) Pa of the wind flow in front of the WFC

The next measurement was performed within the central part of the WFC (Fig. 6). According to the internal dimensions of the wind flow concentrator, the number of measurements was less, namely 5 horizontally and 7 vertically. The bold line shows the profile of the blades in the central part of the WFC. Based on the obtained data, contour graphs in the MathCAD software are constructed, which show the distribution of wind flow velocities (Fig. 6a) and pressures (Fig. 6b) in the central part of the wind flow concentrator.

From the graph (Fig. 6a) it follows that there is a significant increase in the velocity of air masses in the area of the wind turbine blades. The average air velocity in the central part of the wind flow concentrator in the area of the wind turbine blades is about 4.5 m/s, at the inlet wind flow velocity in the channels of the wind flow concentrator of 1 m/s.

Analysis of the obtained pressure field in Fig. 6b shows a significant increase in pressure in the area of the wind turbine blades. The average air pressure in the central part of the wind flow concentrator in the area of the wind turbine blades is about 13.3 Pa.



a) b)

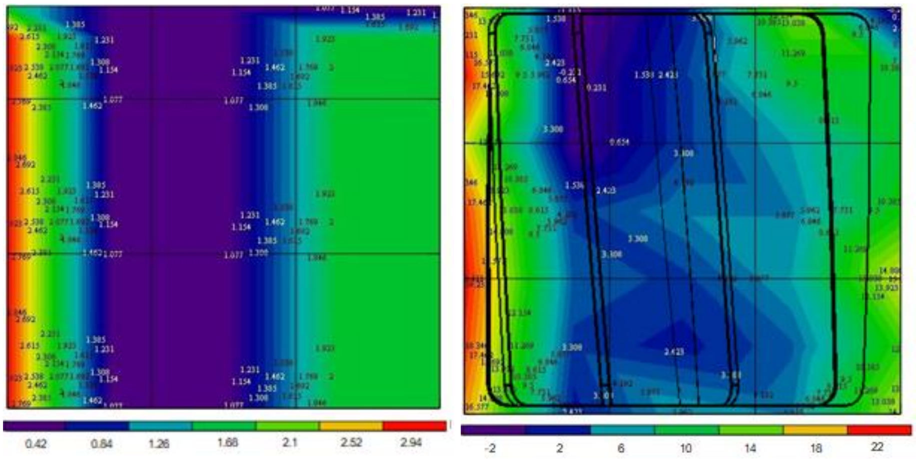
Fig. 6 – Distribution of velocities (a) m/s and pressures (b) Pa of wind flow in the central part of the WFC

Thus, when using the developed design of the WFC in its central part there is a significant increase in air flow velocity in the blades area of the wind turbine rotor. The average air velocity in the central part of the wind flow concentrator in the area of the wind turbine blades is 4 m/s, at an inlet velocity of 1 m/s. As a result of using the design of the wind flow concentrator, when flowing on the rotor of the wind turbine, makes it possible to increase the air flow velocity more than 4 times.

Similar measurements of velocity and pressure fields were performed at the second position of the wind flow concentrator, at its displacement by 30° (Fig. 4b). The measurement results are shown in Fig. 7-10.

The obtained results of experimental studies of the velocity distribution for the position of the WFC at 30° generally correlate with the position of the WFC at 0° (see Fig. 5-6).

The difference lies in the larger values of velocity in the central part of the wind flow concentrator, the average value of which is 4.7 m/s (Fig. 8-9) and a more uniform distribution of air flow velocities in the horizontal section of the working area of the wind tunnel. In addition, for the position of the wind flow concentrator at 30°, the pressure in the central part of the structure is slightly reduced compared to the previous position, and its average value is 8.2 Pa (Fig. 7).

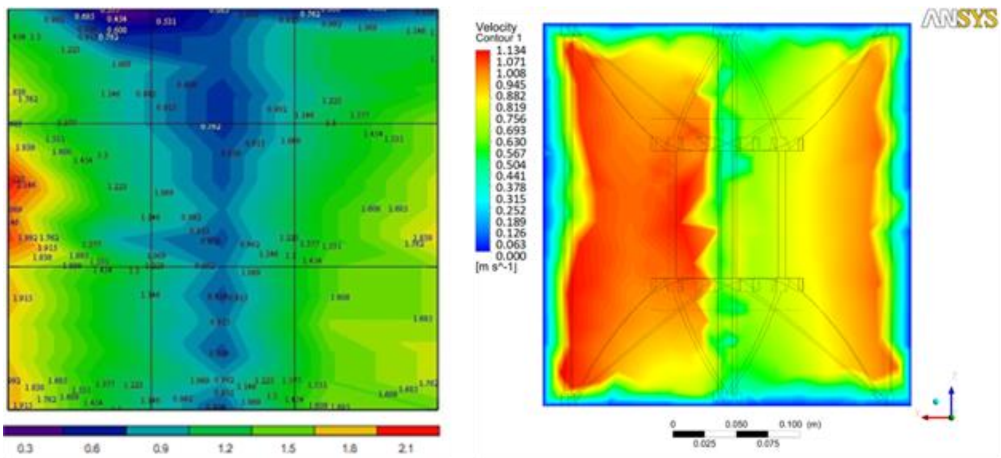


a) b)

Fig. 7 – Pressure distribution (Pa) of wind flow in front of the WFC (a) and in the central part of the WFC (b)

A comparison of the results of numerical simulations (CFD simulation) (*Gorobets V.G. et al., 2021*) of aerodynamic flow in wind turbine with a vertical axis of rotation and a wind flow concentrator at the second position of the concentrator, which corresponds to its displacement by 30° was performed (see Fig. 4b). The results of the comparison for the distribution of air flow velocities when flowing around the wind flow concentrator are shown in Fig. 17-19.

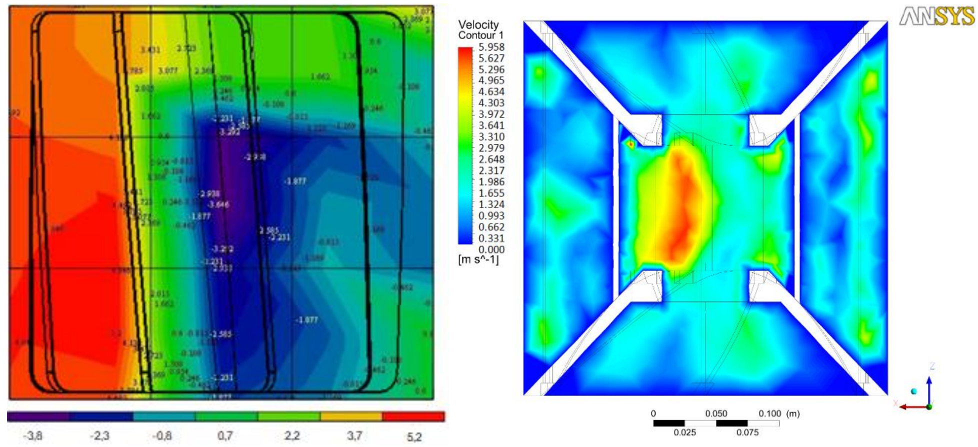
Fig. 8 shows the results of CFD modeling (*Gorobets V.G. et al., 2021*) and experimental data for local velocity distributions in the air flow in front of the WFC. Fig. 9 shows the same results in its central part. Fig. 10 shows the average values of velocities in the cross section of the working area of the wind tunnel obtained by experimental and numerical study. The comparison shows that the air velocity in front of the WFC in numerical calculation is close to 1.09 m/s, at the same time in the experimental data, the average air velocity is 1.03 m/s (Fig. 10). In the central part of the wind flow concentrator the average values of air velocity in numerical simulation are 5.45 m/s, and in experimental studies the air velocity is close to 4.85 m/s (Fig. 10). Estimates show that the error of CFD modeling results in front of the wind flow concentrator does not exceed 5%, and in its central part – 12.3%. Higher values of errors in numerical simulations within the wind flow concentrator are explained by the more difficult nature of the hydrodynamic flow in this area. In general, the obtained results of experimental studies and numerical calculations (*Gorobets V.G. et al., 2021*) are satisfactorily correlated with each other.



a) b)

Fig. 8 – Distribution of wind flow velocity (m/s) in front of the WFC

a) experiment, b) CFD modeling (Gorobets V.G. et al., 2021)



a) b)

Fig. 9 – Distribution of wind flow velocity (m/s) in the central part of the WFC

a) experiment, b) CFD modeling (Gorobets V.G. et al., 2021)

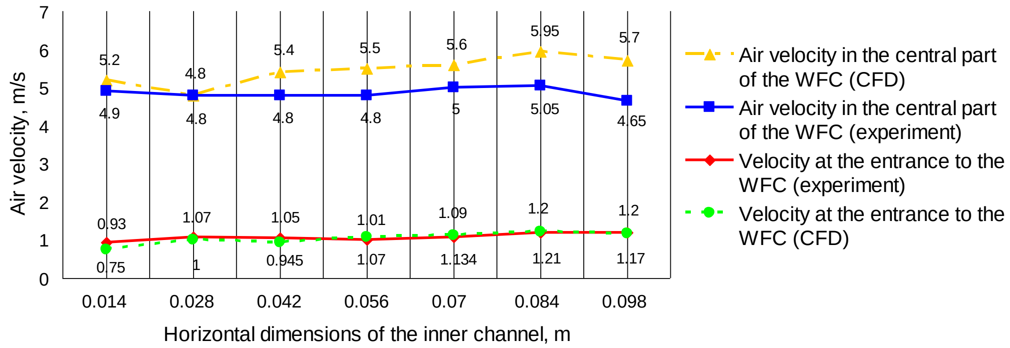


Fig. 10 – Comparison of experimental air velocity data with CFD modeling data *(Gorobets V.G. et al., 2021)*

The results of experimental studies and numerical calculations of hydrodynamics when flowing around the wind flow concentrator of wind turbine with a horizontal axis of rotation make it possible to assess the effectiveness of the suggested device to improve the characteristics of wind turbines. It is known that the efficiency of wind turbines depends on the air flow velocity that flows on the turbine blade:

$$N = C_N N_f \equiv C_N V_{wind}^3 S/2 \tag{1}$$

Where: N - useful power of the wind turbine, N_f - power of the wind flow, V_{wind} - the air flow velocity flowing on the turbine blade, S - the cross-sectional area of the wind turbine wheel.

Thus, even a small increase in air velocity significantly affects the efficiency of the wind turbine. The use of wind flow concentrator makes it possible to significantly increase the velocity V_{wind} as well as the total power of the wind turbine. In the future efficiency assessments and economic calculations of the suggested systems will be carried out. This will achieve an increase in the efficiency of specific structures of vertical-axis wind turbine.

CONCLUSIONS

1. A new design of the wind flow concentrator is proposed, which makes it possible to significantly increase the air flows velocity, flowing on the blades of wind turbines with a vertical axis of rotation.

2. Experimental studies of the hydrodynamic characteristics of the air flow during the flowing around the wind flow concentrator at different positions relative to the flow direction using a wind tunnel were conducted. The fields of velocities, pressures in front of the concentrator and in its central part were found.

3. It is shown that at wind flow velocities of 1 m/s in the central part of the wind flow concentrator the flow velocity when flowing on the wind turbine blade can exceed 4 m/s, which increases the efficiency of wind turbines especially at low air velocities in the environment.

4. The experimental data are compared with the data of numerical modeling of hydrodynamics in the wind flow concentrator and their satisfactory coincidence is obtained.

5. The prospects of using a wind flow concentrator for vertical-axis wind turbines to increase its efficiency and economic profitability are shown.

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