Design and Simulation of Small-Scale Horizontal-Axis Wind Turbine with Diffuser Effect

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Abstract. The article presents the results of the investigation of a rotor assembly of a wind turbine with a horizontal axis of rotation. The rotor is equipped with a diffuser which is an integral part of the power generating unit. The research was carried out by means of the ANSYS Fluent software. The geometry used for the tests is a development version of the construction shown in patent application PL 412553 and is characterised by an adjustable angle setting of the rotor blades. The geometric model was obtained by 3D scanning of the actual rotor using the ZScaner scanner ®700. The calculations were carried out for the selected blade angle of attack from 0° to 90° separately for the version with and without the diffuser. The results from the conducted tests were used to determine the characteristics of the power generated by the turbine as a function of rotor speed. The secondary objective of the tests was to analyse the effect of the diffuser on the power generated by the entire rotor assembly.

1 Introduction

Renewable energy sources, including wind energy, are gaining increasing popularity all over the world. The New Bloom Outlook report, compiled by Bloomberg, shows that 7.8 trillion dollars will be allocated to this type of energy in the next 25 years, while the cost of obtaining a unit of energy from wind will fall by 2050 by 58%. [1].

Small and medium-power home wind turbines generate energy from wind in addition to large-scale wind farms. [2] The basic criterion for the division of turbines is the division due to the position of the axis of rotation. Turbines with the vertical and horizontal axis of rotation are distinguished. Paper [3] presents a comparison of these two structural solutions with attention to their advantages and disadvantages. The analysis of the efficiency of a modern wind turbine with a vertical axis of rotation is presented in [4]. Attention is paid to the design solutions affecting the blade aerodynamic performance and turbine wakes, as well as the aspects requiring further research. It is important to locate the turbine in such a way that the outer objects around the rotor create for him a natural diffuser, whose task is to accelerate the air that hits the rotor. The acceleration of air is aimed at increasing the power generated from the device with the same active surface. It is also possible to equip the turbine with a specially designed external diffuser. This solution was used by the authors of the work [5], in which a turbine equipped with a diffuser in the form of a tube was tested in simulation and experiment. The authors of the work [6] used an aerodynamic tunnel to find the optimal shape of the diffuser, and in addition to assess the effect of the diffuser on the performance of a small wind turbine.

According to the Betz's law, the theoretical maximum efficiency of a wind turbine is 59%. Previous research on wind turbines has been aimed at increasing their efficiency and reducing the unit cost of energy obtained. Both goals are achieved through aerodynamic, constructional and material optimisation. The publication [7] shows how advanced wind turbine design can increase the economic value of electricity generated through wind power. Paper [8] presents methods of optimising the efficiency of wind turbines. An example of the work, which describes the method of increasing the efficiency of a small wind turbine through the use of additional capacitors, is publication [9]. Paper [10] presents the numerical optimisation of the shape of small wind turbine blades with the use of differential evolution, while the paper [11] presents the optimisation with the use of a blade model based on Blade Element Momentum theory. This theory was also used in paper [12] to optimise the distribution of chord and twist angle of small wind turbine blade in order to maximise its Annual Energy Production. Genetic algorithms are also used to optimise the blades due to the increased speed and accuracy of calculations [13, 14]. Two different approaches were used by the authors of the paper [15] in the study of wind turbine blades for sub-scale wake testing. Paper

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[16] presents a multi-criteria optimisation of a wind turbine blade in terms of improving efficiency and reducing noise.

Aerodynamic tests of wind turbines can be conducted by means of simulation using the CFD method or by experimental studies using the wind tunnel. Both approaches were used by the authors of paper [17], in which a wind turbine with a vertical axis of rotation was studied. As a result of the tests, the torque and power characteristics were obtained as a function of rotor speed. Paper [18] presents basic operating parameters of a wind turbine with a vertical axis of rotation as a function of time obtained by means of numerical calculations. A similar study is presented in article [19], in which the results of a small-scale vertical-axis wind turbine performed in a wind tunnel were compared with numerical results obtained from a 3D CFD model.

The authors of work [20] analysed the flow through the rotor of the horizontal axis wind turbine accounting for wakes aerodynamics. The topic of wind turbine wakes was also examined by the authors of work [21] who developed a numerical model of a 3D flow field around the tested turbine, while the authors of publication [22] presented a new analytical wake model to determine the wind velocity distribution downwind of a wind turbine.

The purpose of this work was to examine a small wind turbine equipped with an external diffuser in the form of a ring. Another objective of this study was to determine the influence of diffuser application on turbine efficiency and generated power depending on its load.

2 Research object and methodology

The research facility was prepared based on a 3D scan of the actual construction of a wind turbine rotor assembly. The object used for the tests is the development version of the construction shown in patent application PL 412553 and is characterised by an adjustable angle setting of the rotor blades. The ZScanner ®700 laser scanner was used for 3D scanning. 3D scanning technology employed by this device is described in detail in [23] and [24]. Fig. 1 shows a point cloud view of the points of the scanned part of the turbine rotor assembly with the cover. Paper [23] describes the methodology of creating process a geometric model based on a point cloud. Assuming that it is an object that is axially symmetrical, it was possible to make a model based on a scan of only a part of the rotor. The geometric model was prepared in the CATIA V5 program.

The diameter of the turbine rotor assembly in the version without diffuser is 1.29 m while with the diffuser is 1.64 m. In addition to the air velocity v and its density ρ, the active surface area A of the rotor unit is an important component of the power P generated from wind energy (1).

$$P = 0.5 \cdot \rho \cdot A \cdot v^3 \tag{1}$$

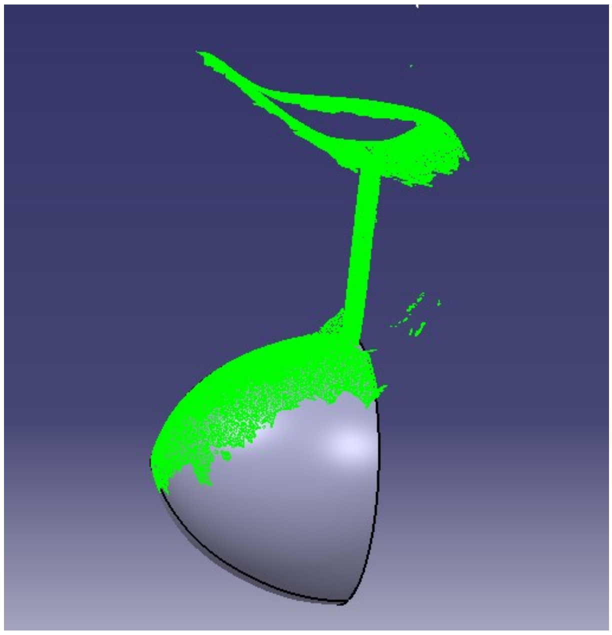

Fig. 1. Point cloud of the scanned part of the turbine rotor assembly with the hub.

The surface area A for the version without diffuser is therefore only 1.3 m^2 while with the diffuser this value increases by 61% and reaches 2.09 m^2, respectively. These values were taken into account during the efficiency calculations of the tested turbine rotor assembly. The computational domain of the considered research object is a cylinder with a diameter of 5 m and length in front of the object equal to 2 m and 3 m behind it. The rotor axis coincides with the main axis of the calculation domain cylinder (Fig. 2).

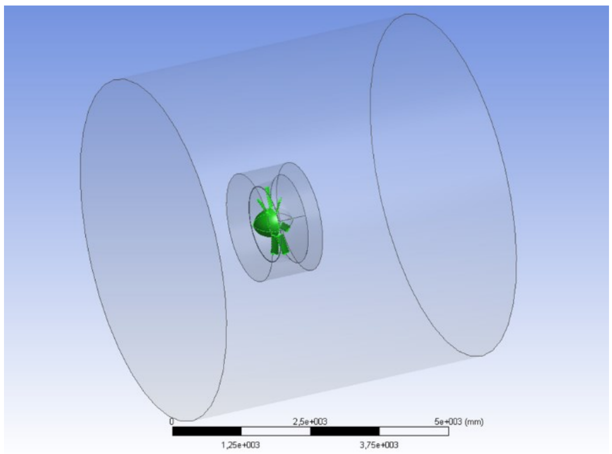

Fig. 2. Calculation domain of the wind turbine rotor.

Fig. 3 shows a grid of a computational model made in the ANSYS Meshing module. The grid was made of elements of the tetrahedrons type with local change of density of elements and the function of inflation. The computational domain grid for geometry with a diffuser was around 6.7 million elements. In the research object three separate regions were selected: diffuser, blades and cover. Thanks to this, it was possible to identify individual

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components of forces and moments acting on these regions.

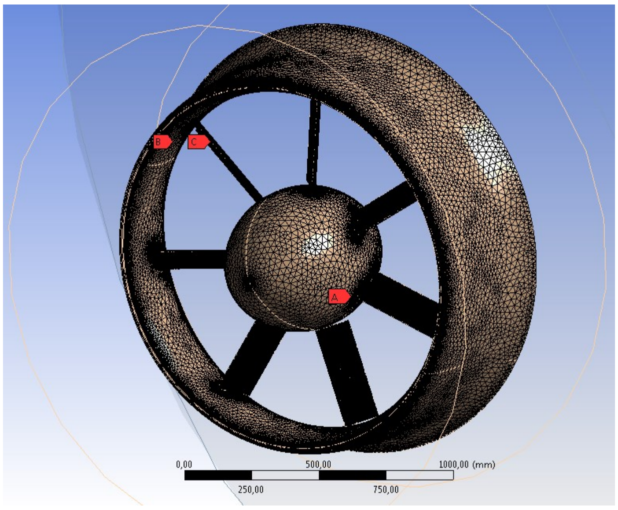

Fig. 3. Generated grid of the wind turbine rotor model.

Fig. 4 shows a detailed view of the generated mesh in the area of attachment of the blade to the diffuser.

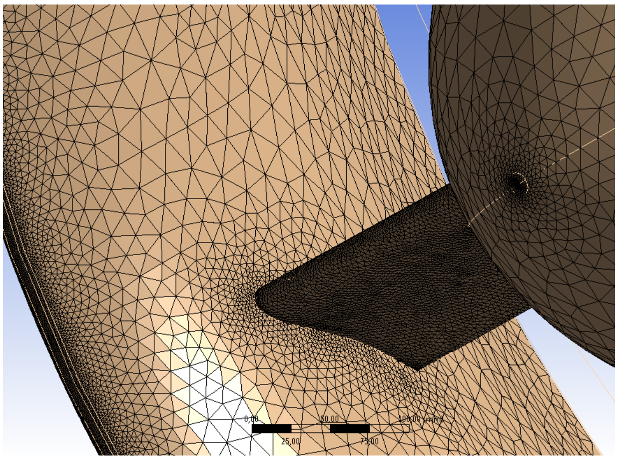

Fig. 4. Generated mesh in the area of attachment of the blade to the diffuser.

The research was conducted by means of the ANSYS Fluent software. The calculations were performed as a pressure-based transient. During the calculations k-ω SST turbulence model was used. On such a defined calculation domain, there were applied the velocity inlet and pressure outlet. The turbulent intensity was set at 5% and the turbulent viscosity ratio was equal to 0.35. The remaining walls, including the surfaces of the turbine rotor are defined as the wall; however, they are distinguished and named basic elements of the construction, *i.e.* blades, cover, diffuser. Rotational motion of the turbine rotor was simulated by Mesh Motion with respect to the longitudinal axis.

3 Results and discussion

In the first part of the tests, the effect of the diffuser on the power of the turbine rotor was checked for initial values of blade angles of 20° and 40°. The angle of attack α was calculated relative to the air flow and not to the plane of rotation. The calculations were made for three values of the velocity of the flowing air: 4 m/s, 8 m/s and 12 m/s. The speed of the turbine rotor was assumed as a parameter. Fig. 5 and Fig. 7 show the power of the turbine rotor as a function of rotational speed for configurations with a diffuser and blade pitch angles of 20° and 40°, respectively. Fig. 6 and Fig. 8 show the turbine rotor power as a function of rotational speed for configurations without a diffuser and the same blade angle of attack.

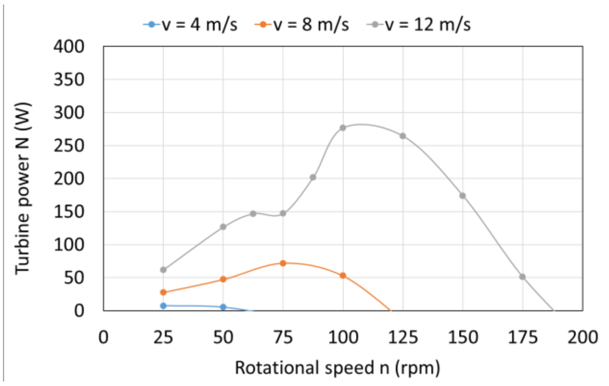

Fig. 5. Turbine rotor power as a function of rotational speed for configuration with the diffuser and α = 20°.

For configurations with a diffuser and α = 20° (Fig. 5), the maximum turbine power for speeds of 4 m/s, 8 m/s and 12 m/s was 7.29 W, 71.78 W and 276.71 W. The maximum values were obtained for speeds of 25 rpm, 75 rpm and 100 rpm respectively.

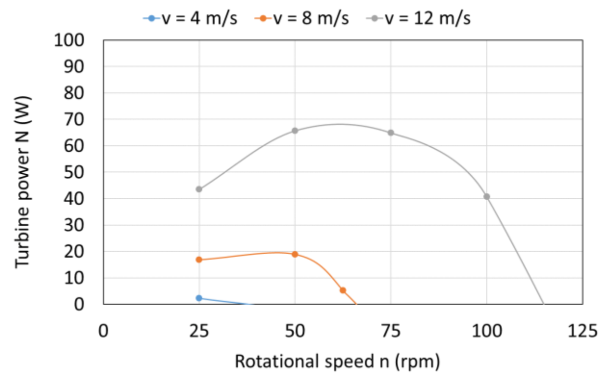

Fig. 6. Turbine rotor power as a function of rotational speed for configurations without diffuser and α = 20°.

For configurations without a diffuser and α = 20° (Fig. 6), the maximum turbine power for speeds of 4 m/s, 8 m/s and 12 m/s was 2.27 W, 18.91 W and 65.66 W respectively at speeds correspondingly equal to 25 rpm, 50 rpm and 50 rpm.

In the case of configurations with a diffuser and α = 40° (Fig. 7), the maximum turbine power for speeds of 4 m/s, 8 m/s and 12 m/s was 25.65 W, 220.69 W and 766.25 W at rotation speeds, respectively 75 rpm, 150 rpm and 200 rpm.

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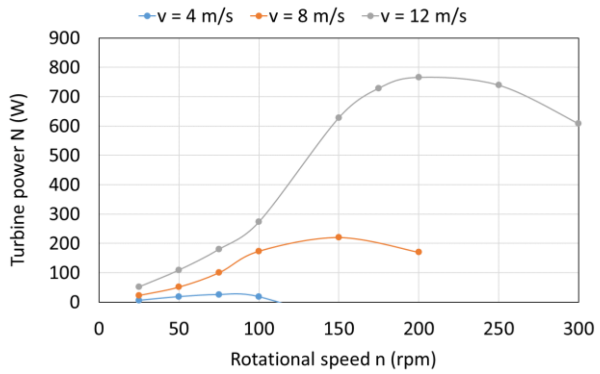

Fig. 7. Turbine rotor power as a function of rotational speed for configurations with the diffuser and α = 40°.

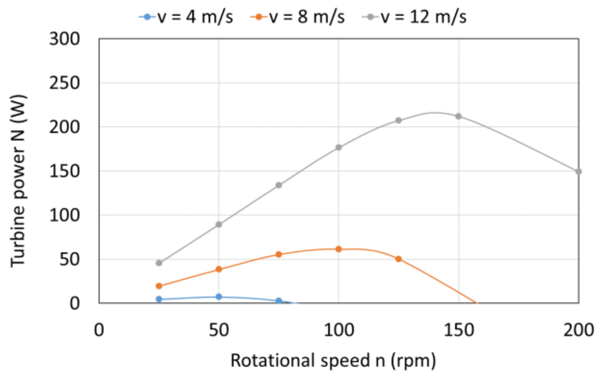

Fig. 8. Turbine rotor power as a function of rotational speed for configurations without diffuser and α = 40°.

For configurations without a diffuser and α = 40° (Fig. 8), the maximum turbine power for velocity equal to 4 m/s, 8 m/s and 12 m/s was 7.14 W, 61.33 W and 211.66 W respectively at 50 rpm, 100 rpm and 150 rpm.

On the basis of the results obtained, the effect of the diffuser on the generated power of the turbine was observed. The increase in power after using the diffuser is significant, and for a blade angle of attack of 20° and an air velocity of 12 m/s, it ranges from 1.42 to 6.8 times – depending on the rotational speed of the rotor. For an angle of 40° and the same air velocity, the diffuser generates power greater from 1.16 to 5.14 times compared to the variant without a diffuser depending on the rotational speed.

In the second part of the study, the calculations were reduced to the analysis of the model with a diffuser and the set of the blade angle was increased by 60° and 80°. A summary of the results for a configuration with a diffuser for different blade angle of attack and air velocity equal to 12 m/s is shown in Fig. 9.

The highest power for rotational speeds in the range from 100 to 250 rpm was obtained for an angle equal to 40°. For the low speed range (25-100 rpm), the powers obtained are similar. A blade angle of attack of 80° turned out to be too large, resulting in a significant power decrease across the entire speed range. For a small blade angle of attack, *e.g.* 20°, there is an abrupt decrease in power after exceeding the speed value of 100 rpm.

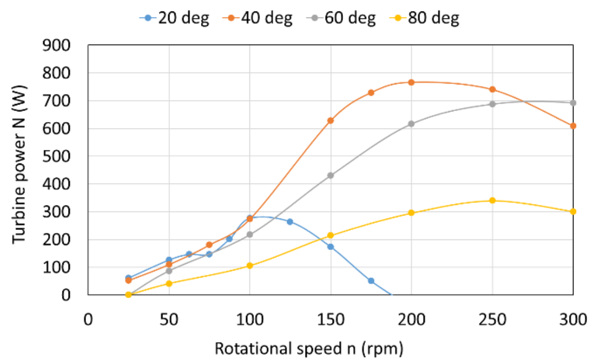

Fig. 9. Turbine rotor power as a function of rotational speed for configuration with the diffuser and v = 12 m/s.

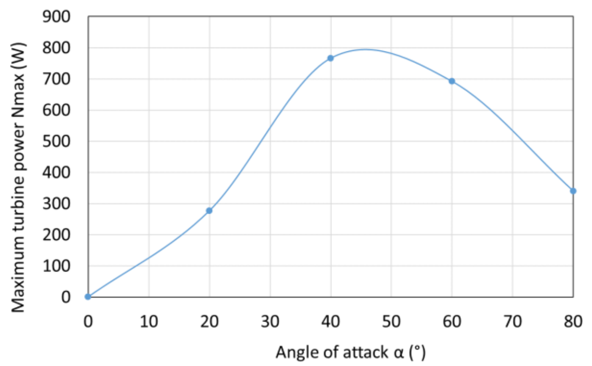

Fig. 10. The maximum power of the wind turbine rotor as a function of the blade angle of attack for the configurations with the diffuser.

Based on the results obtained for the defined configurations with a diffuser, the maximum turbine rotor power values were set as a function of the blade angle of attack (Fig. 10). The analysis of the obtained data shows that for the calculated values of angle of attack the maximum power was obtained for the value equal to 40°.

4 Conclusions

The calculations showed a significant influence of the diffuser on the generated power of the rotor of the tested turbine. The presence of the diffuser results in an increase of the generated power even several times. As the air velocity increases, the power of the turbine rotor increases significantly. For the set blade angle, there is an optimum speed value for which the maximum power of the turbine rotor is achieved.

For the variant with the diffuser, the highest efficiency of 34.5% was achieved at an angle of α = 40°. The variant with an angle of 60° resulted in an efficiency of 31.1%. For comparison, in the model without diffuser and angle α = 40°, an efficiency of only 15.3% was obtained. Removing the diffuser and setting a small blade angle of 20° results in a very low efficiency of 4.8%.

The performed calculations are the first stage in the development of a universal algorithm for controlling the angle of attack of the blades to obtain optimal turbine working conditions.

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