Article

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Aerodynamic optimization of Magnus wind turbine blades using an active deflector

In this work, the optimization of wind turbines is considered by introducing a cylindrical blade with an active deflector. The use of metal (aluminum) deflector, compared with plastic (polypropylene), significantly increased the aerodynamic efficiency of the blade. It is shown that the aluminum deflector reduces the drag force by 18–20 % and increases the lifting force by 2.7 times. The maximum lifting force reached 2.16 N at a wind speed of 15 m/s with an aluminum deflector. In addition, the blade with an aluminum deflector achieved a higher rotation speed — up to 1100 rpm, which is 10 % higher compared to the blade with a polypropylene deflector. The improved performance is due to the high rigidity and minimal deformation of the aluminum material under the influence of air flow. The use of an active aluminum deflector eliminates the need for additional triggers, simplifying the design and reducing operating costs. The results obtained indicate that the use of an active aluminum deflector increases the efficiency of Magnus wind turbines and contributes to the development of renewable energy technologies.

Keywords: cylindrical blade, active deflector, wind turbines, self-starting rotation, aerodynamic characteristics, aluminum deflector, lifting force, drag force, Magnus effect, wind speed, rotation speed, optimization of wind turbine

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Introduction

As global energy demand increases, humanity is facing serious problems related to climate change and environmental degradation. The development and use of renewable energy sources are a necessary solution to ensure global energy security and sustainable development [1]. Among the technologies for generating electricity from renewable sources, wind energy stands out due to its advantages, such as short construction time and low operating costs. According to the Global Wind Energy Council, by the end of 2020, the total installed capacity of the global wind energy industry reached 743 GW [2]. Forecasts show that by 2027, the annual increase in installed capacity may increase significantly, supporting the transition to a more sustainable and environmentally friendly energy future [3–6].

Special attention in this area is paid to various types of wind turbines and the improvement of their designs [7]. Traditionally, wind turbines are divided into horizontal-axial [8] and vertical-axial installations [9]. Horizontal-axial turbines are the most common and efficient at stable wind directions and high wind speeds. However, their large dimensions and the need for complex orientation systems limit their use in urbanized areas [10]. Vertical-axial turbines, on the contrary, are capable of operating efficiently in variable wind directions and have a more compact design, which makes them attractive for use in urban environments and in limited areas. However, their efficiency is often lower, which encourages further research to optimize their aerodynamic characteristics.

One of the innovative directions in the development of wind energy is the use of Magnus wind turbines. These installations use the Magnus effect, based on the interaction of a rotating cylinder with an air flow to generate lift. As a result, such turbines are able to provide efficient operation at low wind speeds and in conditions of turbulence [11, 12].

However, despite the promise of Magnus wind turbines, their widespread use is hampered by a number of technical problems and disadvantages. Recent studies [13–16] indicate the main limitations, such as insufficient lifting force at very low wind speeds, the need for an external drive to initiate rotation of cylindrical blades, which complicates the design and increases operating costs, as well as the complexity of construction and maintenance due to an increase in the number of moving parts.

In a number of papers [11, 12, 15], it was noted that Magnus wind turbines demonstrate reduced efficiency under certain wind conditions and require additional design optimization. For example, researchers have reported the need to use additional triggers to initiate blade rotation [17], which increases the complexity of the system and operating costs.

To solve these problems, it is proposed to introduce an active deflector on a cylindrical blade. A deflector is a device that optimizes airflow to increase thrust and improve the efficiency of a wind turbine (Fig. 1). It interacts with the incoming airflow, creating an additional moment that promotes self-starting rotation of the blade without the need for an electric drive. This simplifies the design, reduces operating costs and increases turbine efficiency by increasing lift and reducing drag.

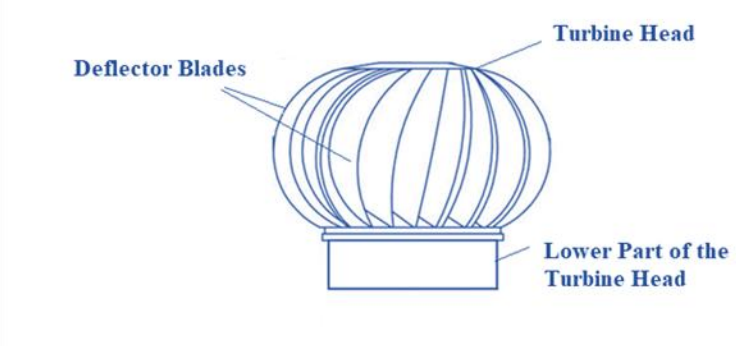


Figure 1. Deflector

The deflector consists of the following main elements: the turbine head, which includes a system of rotating blades; deflector blades located around the head and guiding the airflow to increase aerodynamic efficiency; and the lower part of the turbine head, which serves to connect the structure to the support base, ensuring its stability and functionality.

The principle of operation of the deflector is based on the effect of the incoming air flow on the blades of the active head of the device, which creates a centrifugal force and drives the cylindrical tube. This eliminates the need to use additional triggers. The key advantages of the deflector are simplicity, lightness and cost-effectiveness. The turbine head, structurally resembling a multi-blade vertical-axial rotor, is rigidly connected to the cylinder and spins it due to wind force, increasing the lifting force and aerodynamic efficiency of the installation. For reliable operation in various climatic conditions, deflectors must have strength, durability, wear resistance and low weight; the use of aluminum in the structure allows to reduce weight and increase corrosion resistance.

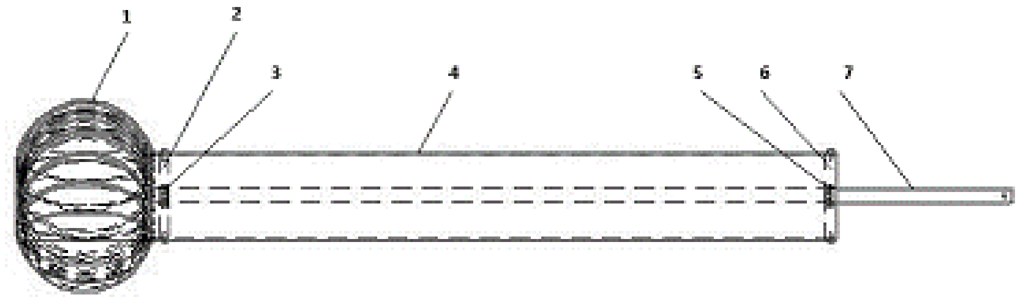
The purpose of this work is to increase the efficiency of Magnus wind turbines by developing and experimentally studying a cylindrical blade with an active deflector made of aluminum. The novelty of the work lies in the use of an active deflector, which provides self-starting rotation of the blade without the use of additional starting mechanisms, as well as in a comparative analysis of the aerodynamic characteristics of blades with deflectors made of different materials to determine the optimal solution.

Experimental methodology

As part of the study, a combined blade was developed, made in the form of a cylinder with a deflector. Experimental studies were conducted in the laboratory “Aerodynamic measurements” of the Scientific Center “Alternative Energy” of the Karaganda Buketov University. The object of the study was installed in the working area of the T-1-M wind tunnel, where experimental measurements were performed.

The experimental sample of a cylindrical blade consists of a cylinder equipped with a deflector. The deflector lobes open under the influence of air flow, which ensures the independent start of rotation of the cylindrical blade without the need for additional starting mechanisms (Fig. 2). The cylindrical blade under study consists of a rotating cylinder (*4*) and an active rotary deflector (*1*) mounted on an iron rod (*7*), which is attached to a radial disk (not shown) of the horizontal axis of the wind turbine. Bearings (*3*, *5*) are installed at both ends of the rotating pipe using mounting discs (*2*, *6*). The principle of operation of the blade is as follows: due to the rotational action of the deflector (*1*), under the influence of an incoming air flow, the cylindrical pipe (*4*) begins to rotate through the bearings (*3*), without using an electric drive. At the same time, a lifting force is created due to the Magnus effect, which triggers the rotation of the blade and, ultimately, drives the wind wheel of the installation.

This design of the deflector allows for autonomous rotation of the entire blade without the use of additional sources for the trigger mechanism. The deflector is made in the shape of a ball with 24 separate lobes, which are attached on one side to a cylindrical pipe, and on the other to a round base using bolts.



1 — active deflector; *2*, *6* — bearing mounting discs; *3*, *5* — bearings;
4 — rotating pipe; *7* — iron pipe for mounting the blade

Figure 2. Diagram of a laboratory sample of a cylinder with an active rotary deflector element

Geometric parameters of a cylindrical blade with a deflector in Table 1.

Table 1

Parameters of a cylindrical blade with a deflector

Parameter	Value	Unit of measurement
Deflector radius (R_1)	0.05	m
Radius of the cylinder (R_2)	0.025	m
Cylinder length (L)	0.205	m
Deflector area (S_1)	0.00785	m²
Cylinder area (S_2)	0.01025	m²
Total cross-sectional area (s_1)	0.0181	m²
Kinematic viscosity (v)	0.0000149	m²/s
Density (ρ)	1.21	kg/m³

To conduct a comparative analysis of the efficiency of the blade, a laboratory mock-up of a cylindrical blade with an active deflector made of metal (aluminum) and plastic (polypropylene) was made (Figs 3 and 4).

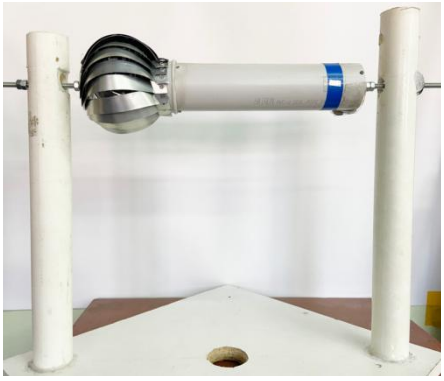


Figure 3. Experimental layout of a cylindrical blade with a metal active deflector (made of aluminum)

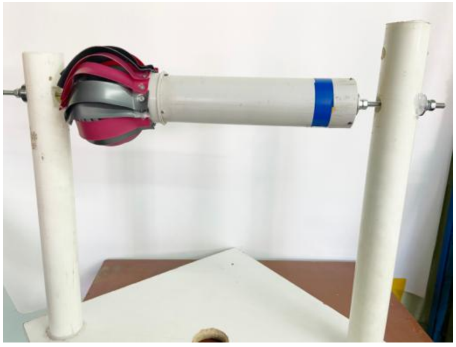


Figure 4. Experimental layout of a cylindrical blade with a plastic active deflector (made of polypropylene)

Table 2 presents a comparative analysis of the main characteristics of aluminum and polypropylene used in the manufacture of an active deflector [18].

Table 2

Comparative characteristics of aluminum and polypropylene for an active deflector

Characteristic	Aluminum	Polypropylene
Density, kg/m^3	2700	900
The thickness of the material in the deflector, mm	0.2	0,5
Tensile strength, MPa	70–700 (depending on the alloy)	20–40
Modulus of elasticity, GPa	69	1,5–2
Stiffness and deformation under load	High rigidity, minimal deformation	Low rigidity, prone to deformation
Aerodynamic properties	Lowdrag, highlift	High drag, lowlift
Weight at the same size	Heavier due to higher density, offset by a smaller thickness	Lighter, but requires more thickness for durability

As part of the study, experimental models of a cylindrical blade with an active deflector made of aluminum and polypropylene were made for comparative analysis.

According to the standard [19], an analysis of measurement uncertainty was carried out (1–4). In our case, the values of the drag force and lift (Y) were not measured directly, but were calculated using N other values X_1, X_2, X_3 and X_N according to the functional dependence (1):

$$Y = f\left(X_1, X_2, X_3 \ldots X_N\right). \tag{1}$$

For each input parameter X_i, participating in the model, the estimate is made taking into account its value x_i and the standard uncertainty x_i and the standard uncertainty $u(x_i)$. The estimate of the input quantities (x_1, x_2 ... x_n) is their mathematical expectation, and the standard uncertainty $u(x_i)$ is the standard deviation.

The methods for estimating standard uncertainties depend on the available information about the value of X_i and can be performed according to type A or type B. The standard uncertainty of type A is calculated using the formula (2):

$$U_A = \left(F\sqrt{\frac{\sum_{i=1}^{n}\left(F_i - \bar{F}\right)^2}{n(n-1)}} \right), \tag{2}$$

where, F_i — measurement of the value; n — number of measurements; $\bar{F}$ — the arithmetic mean, calculated as $\bar{F} = \frac{\sum_{n-1}^{n} F_i}{n}$.

The standard uncertainty of type B is estimated based on non-statistical information using the formula (3):

$$U_B = \left(F\right) = \frac{\Delta F}{\sqrt{3}}, \tag{3}$$

where, $\pm\Delta F$ are the limits of the permissible error of the device.

The total standard uncertainty is determined by the following expression (4):

$$u_c = \sqrt{\sum_{i=1}^{n} k_i u_i^2}, \tag{4}$$

where, u_i is the standard uncertainty of the i-th factor; k_i is the sensitivity coefficient or weighting factor for this factor; n is the total number of uncertainty factors.

This approach allows you to take into account all possible sources of errors and provides a reliable assessment of measurement accuracy.

In engineering practice, the formula (5) is widely used to calculate the lift coefficient:

$$C_y = \frac{\Delta F_y}{\rho \cdot \frac{u^2}{2} \cdot S} \text{ or } C_y = \frac{2F_y}{\rho u^2 \cdot S}. \qquad (5)$$

The following expression was used to calculate the drag coefficient (6):

$$C_x = \frac{\Delta F_x}{\rho \cdot \frac{u^2}{2} \cdot S} \text{ or } C_x = \frac{2F_x}{\rho u^2 \cdot S}, \qquad (6)$$

where, ΔF_x — the drag force, [N]; ΔF_y — lifting force, [N]; ρ — the air density, [kg/m^3]; u — the air flow velocity, [m/s]; S — the area of the midsection, [m^2].

To determine the Reynolds number characterizing the ratio of inertial forces to viscosity forces, the formula was used (7):

$$\mathrm{Re} = \frac{U \cdot D}{\nu}, \qquad (7)$$

where D is the characteristic linear size of the stream lined body; ν is the kinematic coefficient of viscosity.

Results and Discussion

Aerodynamic laboratory experiments were carried out to study aerodynamic forces depending on the flow velocity (3–15 m/s). The dependence of the drag force on the wind speed for two samples of blades is shown in Figure 5. Figure 6 shows how wind speed affects the lifting force of the blade.

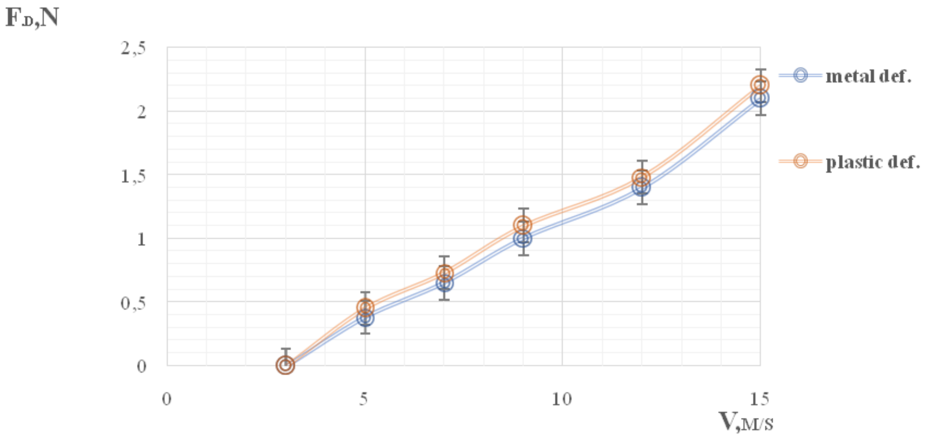


Figure 5. Comparison of the values of the drag forces of the blades with deflectors made of various materials

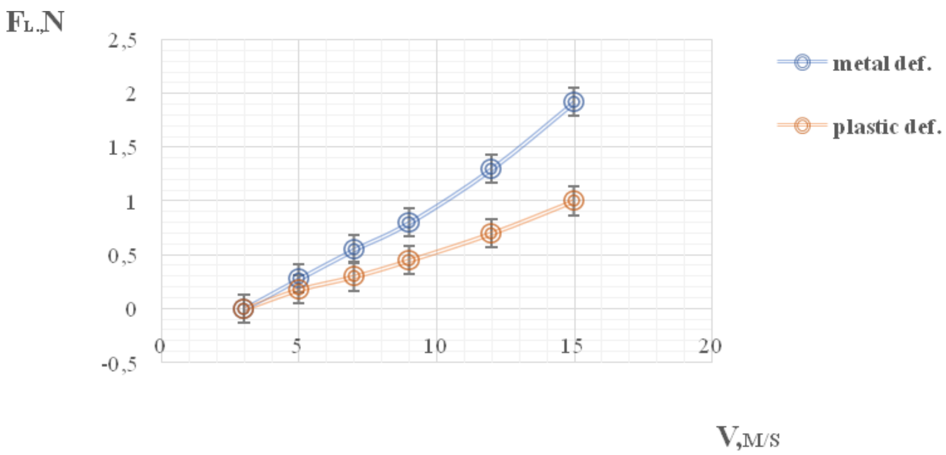


Figure 6. Comparison of the values of the lifting forces of the blades with deflectors made of various materials

As can be seen from the drawings, the blade sample with a metal deflector has the best aerodynamic performance. The drag force of the sample with a metal deflector is almost 18–20 % lower than that of the sample with a plastic deflector, while the maximum drag force was about 2.21 N at a wind speed of 15 m/s. The explanation for this is the difference in the thickness of the materials used for the deflector, i.e., the thickness of the metal is about 0.2 mm, while the thickness of the plastic is 0.5 mm, which is almost 2 times higher. It is known that the thinner the material, the lower the drag.

In the speed range of 2–14 m/s, the lifting force for a metal deflector exceeds that for a plastic deflector. The lift value of a blade with a metal deflector is 2.7 times higher than that of a blade with a plastic deflector. The maximum lifting force of the blade with a metal deflector was 2.16 N. The data indicate a higher aerodynamic efficiency of the metal deflector, which may be due to its geometric stability at high speeds.

An analysis of measurement uncertainty (formulas 1–4) was carried out in order to find the true measurement value, and measurement errors were calculated (Tables 3–6).

Table 3

Results of calculating the uncertainty of the drag of a metal layout

V, m/s	Arithmetic mean.	Uncert. A	Uncert. B	Total uncertainty	Standard deviation	Confidence interval	Error rate
5	0.40	±0.01	±0.02	±0.02	0.02	0.02	7.13
7	0.57	±0.02	±0.03	±0.03	0.02	0.02	6.98
9	0.99	±0.01	±0.05	±0.05	0.03	0.03	7.10
12	1.41	±0.01	±0.06	±0.06	0.04	0.05	7.08
15	2.09	±0.01	±0.10	±0.10	0.07	0.08	7.11

Table 4

Results of calculating the uncertainty of the lifting force of a metal layout

V, m/s	Arithmetic mean.	Uncert. A	Uncert. B	Total uncertainty	Standard deviation	Confidence interval	Error rate
5	0.27	±0.01	±0.01	±0.01	0.03	0.03	7.04
7	0.55	±0.02	±0.03	±0.03	0.03	0.03	6.96
9	0.79	±0.02	±0.04	±0.04	0.02	0.02	7.07
12	1.29	±0.01	±0.06	±0.06	0.03	0.03	7.10
15	1.90	±0.01	±0.09	±0.09	0.03	0.03	7.13

Table 5

Results of calculating the uncertainty of the drag of a plastic layout

V, m/s	Arithmetic mean.	Uncert. A	Uncert. B	Total uncertainty	Standard deviation	Confidence interval	Error rate
5	0.45	±0.01	±0.01	±0.01	0.03	0.03	7.13
7	0.73	±0.02	±0.01	±0.01	0.03	0.03	7.10
9	1.10	±0.02	±0.02	±0.02	0.03	0.03	6.98
12	1.48	±0.01	±0.04	±0.04	0.03	0.04	7.05
15	2.20	±0.02	±0.05	±0.05	0.04	0.05	6.98

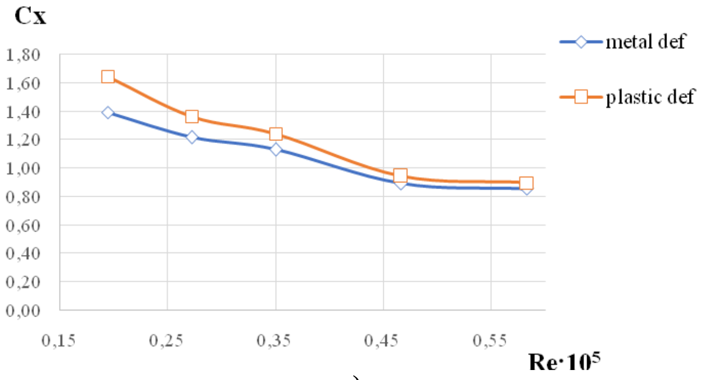
Table 6

Results of calculating the uncertainty of the lifting force of a plastic layout

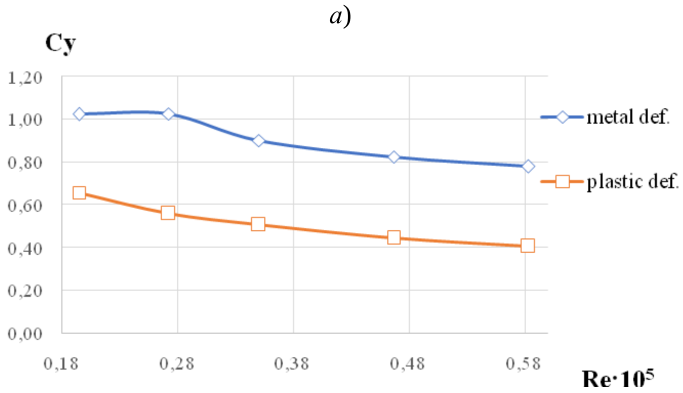
V, m/s	Arithmetic mean.	Uncert. A	Uncert. B	Total uncertainty	Standard deviation	Confidence interval	Error rate
5	0.19	±0.02	±0.01	±0.01	0.03	0.04	7.01
7	0.26	±0.01	±0.01	±0.02	0.03	0.04	7.05
9	0.44	±0.02	±0.02	±0.02	0.03	0.03	6.98
12	0.72	±0.01	±0.03	±0.03	0.02	0.02	7.13
15	0.99	±0.00	±0.05	±0.05	0.03	0.03	6.97

As can be seen from Figures 5 and 6, the uncertainty for both drag and lift is shown in the form of vertical stripes, but they are omitted in the following figures for clarity. Tables 3–6 show that the error was about 7 %, which indicates the high accuracy of the experimental studies.

Figures 7(*a*) and 7(*b*) below show the dependencies of the aerodynamic coefficients on the Reynolds number.



a)



b)

a — coefficient of drag force; *b* — coefficient of lift

Figure 7. Dependence of aerodynamic coefficients on the Reynolds number

The drag coefficient of a blade with a metal deflector is on average 15 % less than that of a blade with a plastic deflector, which indicates lower aerodynamic losses in a metal deflector. The maximum coefficient value for a plastic deflector was 1.6 at $Re = 0.15 \cdot 10^5$, while for a metal deflector it reached only 1.4 under the same conditions. When comparing the obtained results of the drag coefficient with data from other authors, it was found that a cylinder with a metal deflector has a drag coefficient 37–40 % higher than that of conventional cylinders [17], but 35–36 % less than that of cylinders with a plate [20]. Conventional cylinders with a maximum Reynolds number have a drag coefficient of about 1 and do not create significant lift, whereas cylinders with a plate have a coefficient of about 1.9 due to turbulence caused by their geometric features.

The lift coefficient of a metal deflector is on average 1.7 times higher than that of a plastic one. The maximum value for a metal deflector was 1.1 at $Re = 0.18 \cdot 10^5$, whereas for a plastic deflector it was only 0.65. These data confirm the higher aerodynamic efficiency of the metal deflector, which is probably due to its rigidity and stable shape when exposed to air flow. Comparing the results with a cylinder with a rough surface [14], a cylinder with a rough surface demonstrates a 31 % higher lift coefficient on average than a cylinder with a metal deflector at the same air flow rates. However, as the air flow velocity increases, the lift coefficient of a cylinder with a rough surface gradually decreases, reaching a value of 0.23 at a speed of 15 m/s, whereas a cylinder with a metal deflector has more stable dynamics and a value of 0.29 at the same speed, which is 15 % higher. This indicates a more uniform aerodynamic efficiency of deflector cylinders, which can be an advantage when used in conditions of variable air flow velocities, where lift stability is important.

Figure 8 shows the effect of wind speed on the number of revolutions.

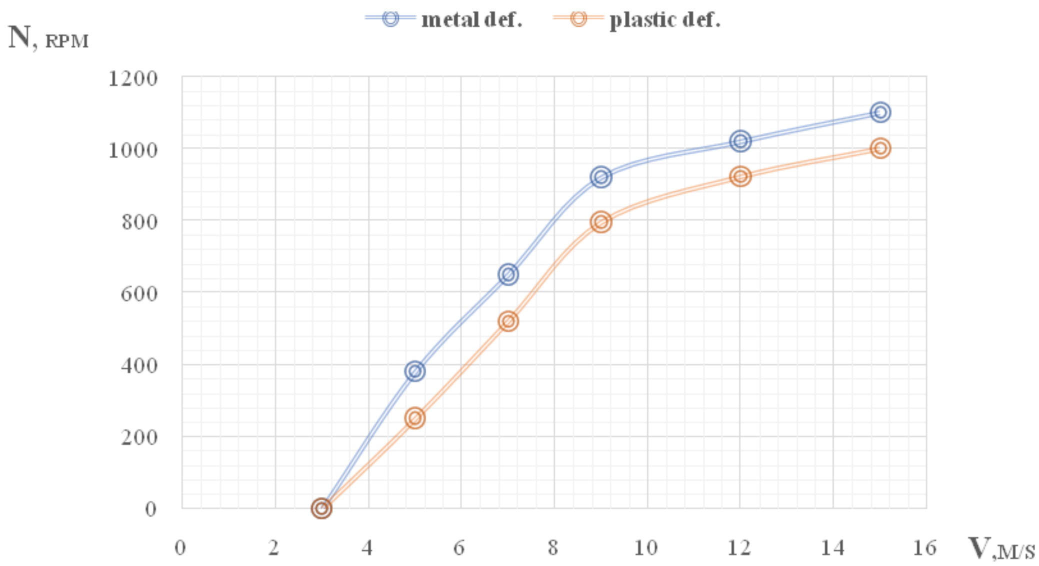


Figure 8. The effect of wind speed on the number of blade rotations

During the comparative analysis, it was determined that the blade with a metal deflector has a higher rotation speed, which at v = 15 m/s is N = 1100 rpm, which is 10 % higher than the rotation speed of blades with a plastic deflector. This indicates that the metal deflector contributes to a more efficient use of wind energy. The rigidity of the aluminum deflector allows you to maintain stable aerodynamic quality, which is especially important at high wind speeds, when the plastic can be subject to significant deformation.

From the conducted studies, it is shown that a cylindrical blade with an aluminum deflector, being poorly deformable, rigid and retaining a given shape, has relatively higher aerodynamic parameters.

Conclusion

This article discusses the problem of optimizing wind turbines by introducing a cylindrical blade equipped with an active deflector. The characteristic features of this design are analyzed; special attention is paid to its ability to initiate rotation without additional triggers due to the interaction of the deflector with the air flow. The conducted research has established that the introduction of a cylindrical blade with an active aluminum deflector significantly increases the efficiency of wind turbines. The use of an aluminum deflector reduces the drag force by 18–20 % and increases the lifting force by 2.7 times compared to the polypropylene analog. The maximum lifting force reached 2.16 N at a wind speed of 15 m/s, and the blade rotation speed increased to 1100 rpm, which is 10 % higher than that of a blade with a polypropylene deflector.

The improved aerodynamic characteristics are due to the high rigidity and minimal deformation of the aluminum material, which ensures more effective interaction with the air flow. The use of an active aluminum deflector allows you to eliminate additional triggers, simplifying the design and reducing operating costs.

The results obtained confirm the prospects of using active aluminum deflectors in the design of Magnus wind turbines to increase their efficiency and develop renewable energy technologies.

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Магнус желтурбинасының қалақшаларына белсенді дефлекторды пайдаланып, аэродинамикалық оңтайландыру

Жұмыста цилиндрлік қалақшалы белсенді дефлекторымен енгізу арқылы желтурбиналарин оңтайландыру карастырылған. Пластикпен (полипропилен) салыстырғанда, металл (алюминий) дефлекторын қолдану қалақшаның аэродинамикалық тиімділігін едәуір арттырады. Алюминий дефлекторы кедергі күшін 18–20 %-ға төмендетіп, көтеру күшін 2,7 есеге арттыратыны көрсетілді. Максималды көтеру күші 15 м/с жел жылдамдығында алюминий дефлекторымен 2,16 Н-ға жетті. Сонымен қатар, алюминий дефлекторымен қалақша жоғары айналу жылдамдығына жетті, яғни 1100 айн/мин дейін, бұл дегеніміз полипропилен дефлекторы бар қалақшамен салыстырғанда 10 %

жоғары. Жақсартылған көрсеткіштер алюминий материалдың жоғары қаттылығы мен ауа ағынының әсерінен минималды деформациясына байланысты. Белсенді алюминий дефлекторын қолдану қосымша электр қозғалтқыштарының қажеттілігін жояды, құрылымды жеңілдетіп, пайдалану шығындарын төмендетеді. Алынған нәтижелер белсенді алюминий дефлекторын қолдану Магнус жел турбиналарының тиімділігін арттыратынын және жаңартылатын энергия технологияларын дамытуға ықпал ететінін көрсетеді.

Кілт сөздер: цилиндрлік қалақша, белсенді дефлектор, жел турбиналары, өздігінен іске қосылатын айналу, аэродинамикалық сипаттамалар, алюминий дефлекторы, көтеру күші, маңдайлық кедергі күші, Магнус әсері, жел жылдамдығы, айналу жылдамдығы, жел турбинасын оңтайландыру

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Аэродинамическая оптимизация лопастей ветровых турбин Магнуса с использованием активного дефлектора

В данной работе рассматривается оптимизация ветряных турбин путем введения цилиндрической лопасти с активным дефлектором. Использование металлического (алюминиевого) дефлектора, по сравнению с пластиковым (полипропиленовым), значительно повысило аэродинамическую эффективность лопасти. Показано, что алюминиевый дефлектор снижает силу сопротивления на 18–20 % и увеличивает подъемную силу в 2,7 раза. Максимальная подъемная сила достигла 2,16 Н при скорости ветра 15 м/с с алюминиевым дефлектором. Кроме того, лопасть с алюминиевым дефлектором достигла более высокой скорости вращения — до 1100 об/мин, что на 10 % выше по сравнению с лопастью с полипропиленовым дефлектором. Улучшение характеристик обусловлено высокой жесткостью и минимальной деформацией алюминиевого материала под воздействием воздушного потока. Использование активного алюминиевого дефлектора устраняет необходимость в дополнительных электродвигателях, упрощая конструкцию и снижая эксплуатационные расходы. Полученные результаты свидетельствуют о том, что использование активного алюминиевого дефлектора повышает эффективность ветровых турбин Магнуса и способствует развитию технологий возобновляемой энергетики.

Ключевые слова: цилиндрическая лопасть, активный дефлектор, ветряные турбины, самозапускающееся вращение, аэродинамические характеристики, алюминиевый дефлектор, подъемная сила, сила лобового сопротивления, эффект Магнуса, скорость ветра, скорость вращения, оптимизация ветряной турбины

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