UDC 533.6
DOI: 10.15587/1729-4061.2023.277759

DETERMINATION OF THE AERODYNAMIC CHARACTERISTICS OF A WIND POWER PLANT WITH A VERTICAL AXIS OF ROTATION

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Wind energy is a commercially proven and rapidly developing type of electricity generation. Wind power plants with a vertical axis are more attractive and better suited for use in cities and urban environments where wind flow is less predictable compared to widespread wind power plants with a horizontal axis of rotation. This makes them a much better choice for both ground installation and/or for mounting on buildings and roofs that would otherwise limit the installation of higher horizontal turbine structures.

The paper describes an experimental study of the drag force and its coefficient for wind turbines with a vertical axis of rotation. The object of the study is a laboratory model of a wind turbine with blades made in the form of rotating cylinders with a fixed blade. Experimental studies were carried out in the T-1-M wind tunnel, measurements of aerodynamic force were carried out using three-component scales. A distinctive feature of the work is the combined use of the lifting force of the cylinders, as well as the lifting force of the fixed plate. Due to this solution, when comparing with existing wind turbines with a vertical axis of rotation, it was found that the wind turbine in question prevails by 25–100 % in the number of revolutions. The dependences of the drag force on the flow velocity and the drag coefficient on the Reynolds number from 1·104 to 4·104 are obtained. An uncertainty analysis was also carried out in order to determine the uncertainty by type A, B and the total uncertainty, from which it was found that the measurement error was 1.13 %. The field of the practical application of the results obtained in laboratory studies will be useful in the development of prototypes of wind turbines with a vertical axis of rotation

Keywords: aerodynamics, flow, combined blade, flow velocity, drag force, thrust force

Received date 08.02.2023
Accepted date 14.04.2023
Published date 28.04.2023

How to Cite: *Tanasheva, N., Tleubergenova, A., Dyusembaeva, A., Satybaldin, A., Mussenova, E., Bakhtybekova, A., Shuyushbayeva, N., Kyzdarbekova, S., Suleimenova, S., Tussypbayeva, A. (2023). Determination of the aerodynamic characteristics of a wind power plant with a vertical axis of rotation. Eastern-European Journal of Enterprise Technologies, 2 (8 (122)), 36–43. doi: https://doi.org/10.15587/1729-4061.2023.277759*

1. Introduction

One of the most important features of the development of the modern world is the emphasis of the world community on the problems of rationality and efficiency of the use of energy resources, the introduction of energy-saving technologies and the search for renewable energy sources. The growing need of mankind for energy resources leads to the need to search for alternative sources of energy supply and their widespread use.

Among the types of alternative energy, wind energy is distinguished by its high efficiency and accessibility. Over the past few decades, wind power has emerged in a number of countries into separate branches of energy farms that successfully compete with traditional energy [1].

2015 was a significant year for Denmark, in which more than 40 % of electricity was generated from wind energy (the highest volume ever recorded worldwide) [1], while Ireland, Portugal and Spain produce approximately 20 % of their

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electricity from wind energy, and 11 of the 28 EU member states had a share of wind energy of 10 % of the total amount of energy generated. These figures prove that over the past 30 years, wind power has become a major player in the field of electricity production worldwide [1], increasing from only 1.3 GW in 1986 to about 490 GW (total global volume) by 2016 (during this period, global electricity consumption increased from 8,978 TWh [1] to 21,191 TWh), of which approximately 140 GW is accounted for by the European Union.

The main attention is paid to wind power installations (wind turbines) of medium and large capacity as part of electricity distribution and transmission networks [2]. However, at present [3] the world market of small wind turbines is also dynamically developing due to mass consumers, which include low-rise construction facilities, farms, fishing artels and hunting grounds, remote monitoring systems, road lighting systems, telecommunications equipment and other autonomous consumers of electric energy. In this regard, an urgent scientific and technical task is the effective use of low wind potential, which consists not only in improving the aerodynamic characteristics of wind turbines [4], but also in increasing the performance of wind turbines as a whole.

One of the wind power plants designed to use low wind potential are wind turbines with a vertical axis of rotation [5]. A vertical-axis wind turbine in comparison with a horizontal-axis wind turbine has obvious advantages such as independence of functioning from the direction of wind flow propagation, which eliminates the need [6] to install additional wind orientation mechanisms, as well as the placement of the installation generator is possible on the foundation of the same installation, which allows you to abandon the powerful, and therefore, as a rule, multi-stage, angular torque transmission. Basically, many works are devoted to the study of aerodynamic features of wind turbines of the Darrieus and Savonius type. But in the meantime, the study of the aerodynamic parameters of a wind turbine with a vertical axis of rotation with blades in the form of rotating cylinders remains relevant.

2. Literature review and problem statement

The location of the shaft and the axis of rotation relative to the horizon determines the classification of wind turbines. A turbine with a shaft mounted horizontally parallel to the ground is known as a wind power plant with a horizontal axis.

The aim of the work [7] was to design and manufacture a wind turbine blade with a vertical axis for use on a small scale. A distinctive feature of the object of study is the exclusion of the yaw engine, because the wind turbine has a vertical axis of rotation. However, there is no data on the experimental test that would prove the effectiveness of operation at low wind speeds.

The authors of the work devoted their research [8] to the development and prediction of the aerodynamic characteristics of a unique wind power plant with opposite rotation along the vertical axis, and the aim of the study was to evaluate the effectiveness of the application of the concept of opposite rotation in the VAWT system while increasing the efficiency of its transformation. The work proves the effectiveness of the technology of reverse rotation to a wind turbine with a vertical axis of rotation, which works well under various operating conditions of wind speed, starting from 5 m/s. But nevertheless, densely populated areas have winds ranging from 3 m/s, which makes this installation not effective at lower wind speeds.

The aim of another study [9] is to design an optimized Darrieus-type wind turbine capable of starting at low wind speeds, which is characterized by a low starting torque compared to the Savonius rotor. A mechanism has been created that allows turning the blades during their rotation to give a relative maximum wind speed and increase the starting torque. It was found that the optimal angle of attack providing the maximum torque is $\alpha=15°$. In the case when one blade falls under the action of the wind flow, the other blades change direction relative to the wind flow, thereby increasing the air resistance, which directly proportionally affects the reduction of lift and efficiency.

The authors of the following work [10], using stereo-PIV methods in an experimental wind tunnel, quantified and analyzed the trace of a small wind turbine immersed in the boundary layer. An interesting fact is the presence of two pairs of counter-rotating vortices at the edges of the trace. But the nature of the behavior of aerodynamic coefficients depending on the Reynolds number remained an unresolved question.

The power increase functions have been proven as one of the methods to increase the performance of wind turbines, especially vertical-axis wind turbines. Studies have shown that with the help of a deflector, a casing or a separate plate, the output power of a wind turbine can be significantly increased [11, 12]. It is also known that by adding geometric shapes of flow amplifiers to the main working blade, it is possible to increase the output characteristics of a wind power plant. For example, by adding plates and profiles of various types, the disruption of the turbulent flow from the end of the blades is reduced. However, these works do not show the nature of the influence of this plate on the aerodynamics of the entire system of blades.

One of such installations is wind turbines with a straight blade and a vertical axis, supplemented by a flat plate deflector [11]. To optimize the position, orientation and dimensions of the deflector, an experimental design method based on the orthogonal Taguchi matrix L16 was used. Various options of the deflector arrangement relative to the axis of rotation of the turbine, with its different geometric and linear dimensions, are investigated. 16 three-dimensional numerical experiments were carried out to evaluate the effect of these parameters on the output power of a wind turbine. The use of a deflector with optimal parameters increased the efficiency of the wind turbine by 16.42 % compared to a conventional turbine. However, the influence of the air flow velocity and the Reynolds number on the flow pattern is not shown, which makes the work not completely finished.

In [12], experimental and numerical tests were carried out to study the aerodynamic effects and the flow field around a flat plate deflector as a power increase device, which is located in the lower part of the forward flow of a micro-H-rotor with a vertical axis of rotation. It follows from the study that the deflector is able to create a high-speed wind in the wake area, which was about 25 % higher compared to the headwind speed. According to the results of laboratory tests, with the optimal position of the deflector, the maximum achieved power factor (CP) increased by 7.4 % compared to a wind turbine without a deflector. Based on this, it is possible to judge the high efficiency of adding an auxiliary geometric element in the growth of wind turbine performance. As can be seen, the authors of the work carried out an extended study of the influence of the deflector on the entire power of the wind turbine, but nevertheless, data on aerodynamic coefficients are not provided.

One of the representatives of wind turbines with a vertical axis of rotation are also installations with blades in the form of rotating cylinders based on the Magnus effect [13]. Compared to wind turbines with propellers, wind turbines with cylindrical blades have a sufficiently high rigidity [13]. But nevertheless, the authors made the base for fixing the blades in the form of a triangle, which creates additional resistance. As you know, round shapes have a small coefficient of resistance.

One of the main features of the Magnus wind turbine is the ability to generate energy at low wind speed [14].

Japanese engineers of the scientific project suggested [15] that the Magnus wind turbine with a vertical axis may be the first wind turbine in the world that can generate electricity even during typhoons, and scientists are currently working and studying its characteristics. But there is no laboratory data yet on the effect of adding a fixed blade on the entire wind turbine system with a vertical axis of rotation of the Magnus type.

Although there are many works concerning wind turbines with round cylinders [16–19], few works describe the configuration and aerodynamic characteristics of wind turbines with a vertical axis of rotation with blades in the form of round cylinders to improve energy characteristics.

In [16], a detailed numerical study of the air flow around a wind turbine with cylindrical blades was performed, but nevertheless, experimental data are not available. The authors of [17] presented the results of the energy parameters of the pilot plant, but the disadvantage is also the lack of dependencies of aerodynamic coefficients. A group of authors of the work [18] performed numerical modeling and calculation of the moment of forces around a spinning wind wheel, but the nature of the effect of the flow on the aerodynamics around the wind wheel is also not given. The authors of the work [19] also performed mathematical modeling, but nevertheless, experimental results are the basis for creating prototypes of wind turbines.

Proceeding from this, an urgent issue is to study the aerodynamic features of wind turbines with a vertical axis of rotation with blades in the form of round cylinders with a fixed blade, designed to direct the wind flow to the blades, thereby ensuring the rotation of the wind wheel and increasing the lifting force.

3. The aim and objectives of the study

The aim of this work is to identify some regularities of the drag force and the coefficient of a wind turbine with a vertical axis of rotation operating on the basis of the Magnus effect. This will allow you, based on the results obtained, to create a prototype of a wind turbine with a vertical axis of rotation with combined blades.

To achieve this aim, the following objectives are accomplished:

– to develop and create a laboratory model of a wind power plant for experimental research. To conduct experimental studies to determine the aerodynamic parameters of the layout under different flow regimes, using a T-1-M wind tunnel and three-component weights;

– to obtain the dependences of the drag force at different revolutions of the combined blades at different values of flow velocities. To carry out an analysis of measurement uncertainty, in order to reasonably establish the limits of permissible discrepancies in measurement results; to obtain the dependences of the drag coefficient of the wind turbine layout on the Reynolds number at different values of the speed numbers;

– to obtain the dependencies of the thrust force of the wind turbine layout on the wind speed, in order to determine the effectiveness of its operation;

– to conduct a comparative analysis of the number of revolutions of the wind wheel of the wind turbine with the existing data of wind turbines of various types by other authors.

4. Materials and methods of research

The object of the study is the problem of determining the aerodynamic coefficients of a wind power plant with a vertical axis of rotation at wind speeds starting from 3 m/s, solved by experimental studies in laboratory conditions using a wind turbine layout and a T-1-M wind tunnel.

The hypothesis of the study is the superiority of the number of revolutions of the studied wind turbine layout with a vertical axis of rotation over the existing traditional wind turbines with a vertical axis of rotation by several times, due to the combination of two different blades (rotating cylinders and fixed blades relative to the wind wheel), which contribute to improving the aerodynamic quality and power of the wind turbine.

For measurements of aerodynamic forces, three-component aerodynamic scales fixed in the working part of the pipe were used. The variation of the flow rate was measured with a Skywatch Atmos cup anemometer. The number of revolutions of cylindrical blades and wind wheels was measured by an AT-8 digital laser phototachometer.

5. Results of the study of the aerodynamic characteristics of a wind power plant

5. 1. Laboratory layout of a wind turbine

In accordance with the task, a laboratory model of a wind turbine with a vertical salt of rotation was developed and created, which was further studied in a wind tunnel.

For the first time, a mock-up of a wind power plant with a vertical axis of rotation with combined blades was used as a test sample (Fig. 1). The combined blade is made in the form of a rotating cylinder with a fixed blade. This solution makes it possible to increase the aerodynamic characteristics of the entire wind turbine due to two lifting forces – the lifting force of the cylinder and the fixed blade. Electric motors are installed on the upper part of each blade to start the rotational movement of the cylindrical blades.

The linear parameters of the wind turbine layout are presented in Table 1.

Fig. 1. Laboratory layout of the wind turbine test sample

Table 1

Linear dimensions of the laboratory layout of the wind turbine test sample

Parameters	Value
Diameter of the wind wheel	20 cm
Diameter of cylinders	4 cm
Length of cylinders	9 cm
Length of the fixed blade	10.5 cm
Width of the fixed blade	3 cm

With the above linear dimensions, a laboratory model of a wind turbine with a vertical axis of rotation was created.

The drag force and thrust were measured in the T-1-M wind tunnel. The diagram of the installed T-1-M wind tunnel in the Laboratory of Aerodynamic Measurements of the Department of Engineering Thermophysics of the E. A. Buketov Karaganda University is shown in Fig. 2.

Special grids and devices installed in the channel of the wind tunnel made it possible to ensure a fairly uniform air flow in the working part along the entire cross section.

Experimental studies have been carried out to determine the aerodynamic parameters of the layout under various flow regimes with variations in flow velocity from 3 to 15 m/s, and the number of revolutions of the cylindrical blades 300, 500 and 700 rpm using a T-1-M wind tunnel and three-component weights.

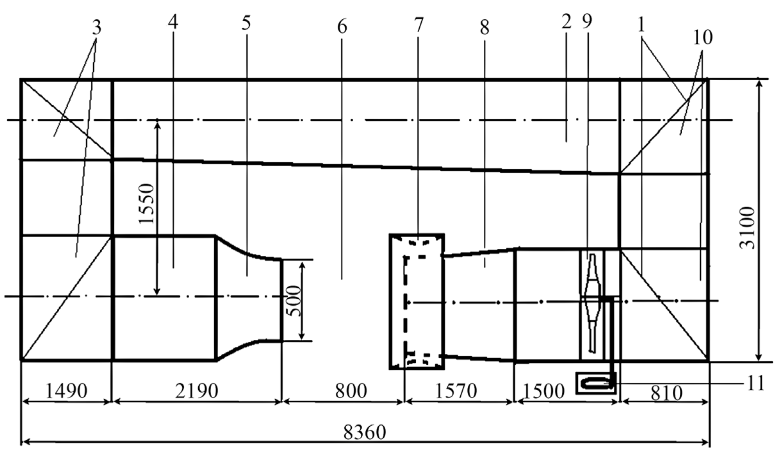

Fig. 2. Diagram of the T-1-M wind tunnel: 1 – guide vanes; 2 – averaged return channel; 3 – rotary part; 4 – through part of the pump; 5 – pump; 6 – working part; 7 – diffuser ring; 8 – diffuser; 9 – cylindrical part of the diffuser; 10 – rotary part of the diffuser; 11 – electric motor

5. 2. Dependence of the drag force and its coefficient. Analysis of measurement uncertainty

In the course of experimental studies, data on the drag force as a function of the air flow velocity were obtained (Fig. 3).

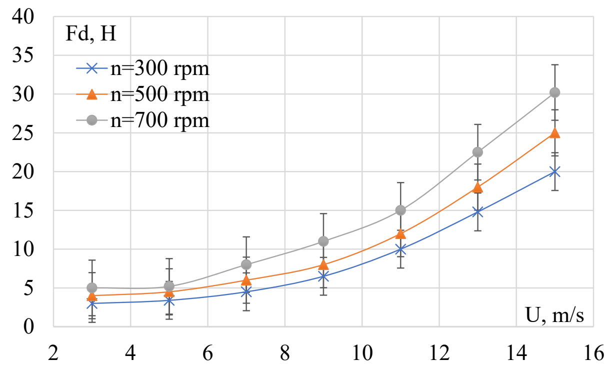

Fig. 3. Dependence of the drag force on the flow velocity at different n

From dependence 3, it can be seen that the drag force increases as the air flow rate increases with an increase in the number of revolutions from 300 rpm to 700 rpm. As the air flow velocity increases, the drag force increases. This is due to the fact that a stream moving at a certain speed acts with a pressure force on the surface of the body to which it is exposed on its way. The magnitude of this force is directly proportional to the flow velocity, which increases with the velocity. And the drag force is directed back to the same pressure force. As the flow velocity increases, the drag force of the model under study increases under the action of the pressure force. Consequently, the drag force increases with increasing air flow velocity.

Below are the results (Tables 2–4) of the uncertainty analysis carried out in accordance with [20].

For each input value of the air flow velocity, uncertainties of type A, B and general uncertainty, as well as a confidence interval, are determined.

Below are the results of calculating the drag coefficient of the wind turbine layout depending on the Reynolds number for a range from 1 to $4{\cdot}10^4$ (Fig. 4).

Table 2

Results of uncertainty analysis at n=300 rpm

V, m/s	Arithmetic mean	Uncertainty by type A	Uncertainty by type B	Total standard uncertainty	Standard deviation	Confidence interval	Error rate, %
3	3.03	±0.019	±0.14	±0.14	0.12	0.13	1.13
5	3.30	±0.029	±0.15	±0.16	0.10	0.11	1.13
7	4.37	±0.038	±0.20	±0.21	0.15	0.17	1.13
9	6.55	±0.029	±0.30	±0.30	0.13	0.15	1.13
11	9.97	±0.010	±0.46	±0.46	0.15	0.17	1.13
13	14.70	±0.029	±0.68	±0.68	0.10	0.11	1.13
15	19.97	±0.010	±0.92	±0.92	0.15	0.17	1.13

Table 3

Results of uncertainty analysis at n=500 rpm

V, m/s	Arithmetic mean	Uncertainty by type A	Uncertainty by type B	Total standard uncertainty	Standard deviation	Confidence interval	Error rate, %
3	3.97	±0.01	±0.18	±0.18	0.15	0.17	1.13
5	4.48	±0.00	±0.21	±0.21	0.18	0.20	1.13
7	5.97	±0.01	±0.28	±0.28	0.15	0.17	1.13
9	7.90	±0.03	±0.36	±0.37	0.10	0.11	1.13
11	11.87	±0.04	±0.55	±0.55	0.15	0.17	1.13
13	18.03	±0.01	±0.83	±0.83	0.15	0.17	1.13
15	25.07	±0.04	±1.16	±1.16	0.15	0.17	1.13

Table 4

Results of uncertainty analysis at n=700 rpm

V, m/s	Arithmetic mean	Uncertainty by type A	Uncertainty by type B	Total standard uncertainty	Standard deviation	Confidence interval	Error rate, %
3	5.03	±0.01	±0.23	±0.23	0.25	0.28	1.13
5	5.10	±0.03	±0.24	±0.24	0.10	0.11	1.13
7	7.97	±0.01	±0.37	±0.37	0.15	0.17	1.13
9	11.03	±0.01	±0.51	±0.51	0.15	0.17	1.13
11	14.97	±0.01	±0.69	±0.69	0.15	0.17	1.13
13	22.40	±0.03	±1.03	±1.04	0.10	0.11	1.13
15	30.17	±0.01	±1.39	±1.39	0.35	0.40	1.13

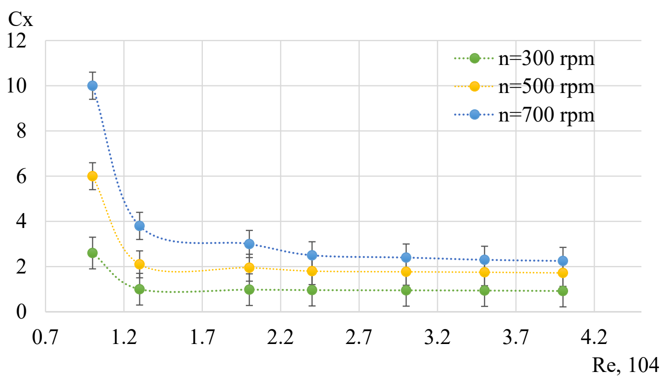

Fig. 4. Dependence of the drag coefficient on the Reynolds number

It can be seen from dependence 4 that as the Reynolds number increases, the drag coefficients decrease. When the airflow flows around the cylinder, a vortex flow is formed outside the cylinders. Vortex flows create the drag of the cylinders. The magnitude of the vortex flow depends on the air flow velocity.

Thus, at a lower flow rate, that is, at a lower Reynolds number ($1\cdot10^4$–$3\cdot10^4$), an increase in the flow velocity intensively reduces the volume of the vortex flow in the reverse flow. There is a rapid decrease in the drag coefficients of rotating cylinders. When the flow velocity is high, that is, the Reynolds number is $4\cdot10^4$ and higher, a strongly vortex region is formed behind the cylinders. Its size is not affected by an increase in the flow rate. Thus, the drag coefficient is stabilized.

5. 3. Dependence of the thrust force of the wind turbine layout

The dependence of the thrust force on the flow velocity at the number of revolutions of the cylinders of a combined wind turbine with a vertical axis of rotation 300 rpm, 500 rpm and 700 rpm is shown in Fig. 5.

It can be seen from dependence 5 that at different wind speeds, the traction force of the wind wheel increases with an increase in the number of revolutions of the blades. Where the accompanying flow on the surface of the rotating cylinder is in the opposite direction to the airflow coming out of the aerodynamic pipeline pump, there is a reduced pressure when the accompanying flow is directed towards the oncoming flow. As a result, the cylinders are displaced towards the lower region under the action of forces in the high-pressure zone. With an increase in the flow velocity, the magnitude of the forces acting on the cylinders decreases in the low-pressure zone and increases in the high-pressure zone.

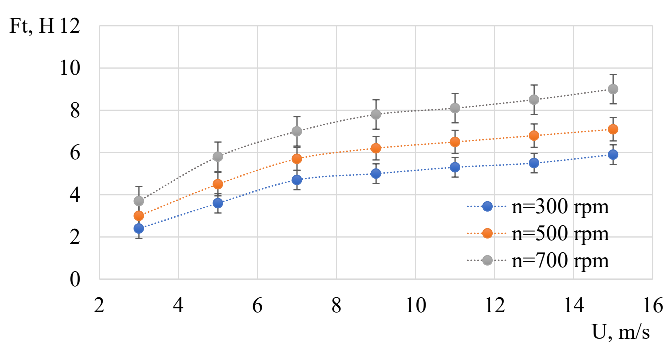

Fig. 5. Dependence of the thrust force of the layout on the wind speed at different numbers of revolutions

Thus, the lifting force of the cylinders in rotational motion also increases. An increase in the lifting force of the cylinders affects an increase in the traction force of the wind turbine. Consequently, as the flow velocity increases, the traction force of the wind turbine with a vertical axis increases. With the number of revolutions of combined wind turbine blades rotating along the vertical axis 300 rpm, 500 rpm and 700 rpm at a flow rate of 15 m/s, the thrust force of 5.8 N, 7.2 N, 9 N has a maximum value.

5. 4. Comparative analysis of the number of revolutions of the wind wheel

A comparative analysis of the number of revolutions of the studied layout with other existing wind turbines with a vertical axis of rotation was also carried out (Fig. 6) [21].

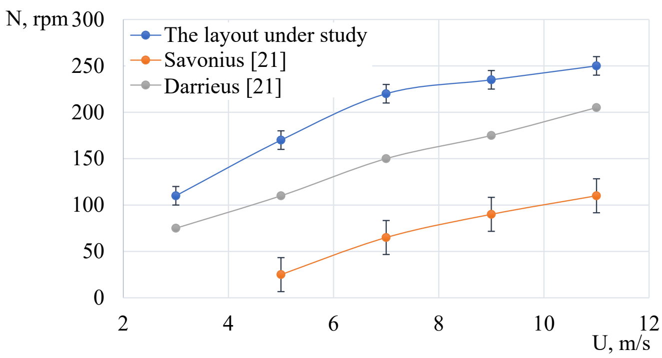

Fig. 6. Comparative dependence of the number of revolutions of different types of wind turbines with a vertical axis of rotation on wind speed

As can be seen from the comparison, the authors' wind turbine gains 25 % more speed than Savonius, as well as 100 % more than Darrieus. Based on this, we can talk about the efficiency of the wind turbine with a vertical axis of rotation based on the Magnus effect.

6. Discussion of the results of the study of the aerodynamic characteristics of a wind power plant

As noted above, the first objective was related to the development and creation of a wind turbine model with combined blades. Existing wind turbines with a vertical axis of rotation have a disadvantage such as electricity generation starting at a speed of 5–6 m/s [4, 6, 7]. But most of the territories of densely populated cities have wind corridors with a wind speed of 3–4 m/s. In this regard, the authors of the work created a new design of a wind turbine with combined blades generating energy starting from 3 m/s. Also, the advantage of the new wind turbine design proposed by the authors of the project is that by supplementing the fixed blades relative to the wind wheel and rotating cylinders, a more complete use of wind energy is provided. This is confirmed by the results we have obtained (Fig. 2).

The second objective was to obtain the dependences of the drag force and its coefficient depending on the flow velocity and the Reynolds number. In comparison with the existing works [10, 11, 16, 17], in the created layout, due to the addition of a fixed blade to the main cylindrical blade, the disruption of turbulent vortices from the blades decreases, the proof of this is a decrease in the value of the drag force and its coefficient, compared with other existing wind turbines (Fig. 3, 4).

The third objective was to obtain the dependencies of the thrust force on the wind flow velocity. A distinctive feature of the studied layout is the presence of a fixed blade, which is also an additional source of thrust force, the obtained thrust force dependences are proof of this (Fig. 5). The magnitude of the forces acting on the cylinders decreases in the low-pressure zone and increases in the high-pressure zone with increasing flow velocity. Thus, the lifting force of the cylinders during rotational movement also increases. An increase in the lifting force of the cylinders affects an increase in the thrust force. Consequently, with an increase in the flow rate, the traction force of the vertical-axis combined wind turbine increases.

The fourth objective was to obtain a comparative dependence of the number of revolutions of various types of wind turbines with the studied layout with a vertical axis of rotation on wind speed (Fig. 6). The results obtained are compared with the results of the authors [21]. It was found that the wind power plant in question with a vertical axis of rotation gains 25–100 % more revolutions compared to existing wind turbines with a vertical axis of rotation. Based on this, it is possible to judge the advantages over traditional wind turbines with a vertical axis of rotation.

The practical significance of the results obtained is determined by the possibility of using them for solving acute problems, both when creating prototypes of wind turbines with a vertical axis of rotation, and in related or interdisciplinary aerodynamic studies of complex combined bodies streamlined by air flow.

Real situations are complex, so they require simultaneous consideration of several application parameters in practice, such as taking into account the influence of temperature and humidity of the environment on the aerodynamic coefficients, and other climatic parameters of air and wind.

As a disadvantage of the study, the lack of a picture of the flow around the model under study in the air flow, from the point of view of studying its aerodynamics, is more preferable, since it gives a real picture of the behavior of the environment behind the layout. In the future, the next stage of the study is planned to determine the moment of forces depending on the speed of the wind flow.

7. Conclusions

1. For the first time, a laboratory model of a wind turbine with a vertical axis of rotation has been created containing combined blades with the following linear dimensions: a wind wheel with a diameter of 20 cm contains installed vertical cylindrical blades with a diameter of 4 cm and a length of 9 cm, to which blades with a length of 10.5 cm and a width of 3 cm are fixed.

2. The dependences of the drag force on the flow velocity are obtained, with the number of revolutions of the rotating cylinders 300 rpm, 500 rpm and 700 rpm, the drag force increases as the air flow velocity increases within 3–15 m/s. The greater the number of revolutions of the rotating cylinders, the higher the wind speed, i.e. it is proved that the difference between the drag force increases by 4–5 %, and at a flow rate of 15 m/s remains (practically) the same and is 30 N. An analysis of the measurement uncertainty was carried out, with the total measurement uncertainty obtained, the error was 1.13 %. The dependence of the drag coefficient on the Reynolds number is also obtained and shown for the number of revolutions of 300 rpm, 500 rpm and 700 rpm when rotating in the vertical direction. The Reynolds number ranged from 1,104 to 4,104. It was found that with an increase in the number of revolutions of rotating cylinders, the Reynolds number also increases, but the drag coefficient decreases.

3. The dependences of the traction force of the wind turbine layout on the wind speed are obtained, in order to

determine the efficiency of its operation. It was found that at different wind speeds, the traction force of the wind wheel increases with an increase in the number of revolutions of the blades. As the number of revolutions of the cylinders increases at a flow rate of 15 m/s, the traction force of 5.8 N, 7.2 N, 9 N acquires a maximum value.

4. A comparative analysis of the number of revolutions of various models of wind turbines with a vertical axis of rotation was carried out, from which it was found that the developed layout prevails over the rotational characteristics of Savonius by 25 % and Darrieus by 100 %.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to the current research, including financial, personal, copyright or any other that could affect the research and the results presented in this paper.

Financing

The work was carried out with the financial support of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (IRN AP14870066 «Development and creation of an energy-efficient combined vertical-axis wind power plant using a gearless low-speed electric generator»).

Data availability

All data is available in the main text of the manuscript.

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