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FLOW PAST THE SAIL BLADE OF A WIND TURBINE

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An experiment to determine the aerodynamic characteristics of a wind turbine with sail blades was conducted on a model. The dependence of the drag and lift coefficients on the dimensionless angle of attack and the number of wind-turbine blades has been determined experimentally.

Keywords: *wind turbine, sail, lift coefficient, drag coefficient, air flow, angle of attack, Reynolds number.*

Introduction. One of the most important unique features of the present world development is a considerable effort devoted by the world community to the problems of rational and efficient use of energy resources, practical application of energy saving technologies, and of the search for renewable energy sources. The growing demand of humanity for energy resources necessitates a wider use of alternative energy supply sources. Primarily they comprise wind-power engineering for the development of which it is extremely important to have reliable information on the wind regime on the territory of the supposed siting of wind-power engineering facilities.

Over the greater part of the territory of Kazakhstan there are zones with low annual average wind velocities. The industry has failed as yet to produce wind-driven motors of small and mean power for such territories, whereas the use of the existing ones is economically unprofitable. In this connection, the development and production of wind-power engineering plants intended for operation with low-velocity wind flows are very urgent for Kazakhstan and correspond to the priorities of science development in the republic.

Wind energy has an enormous potential for reducing the dependence on such traditional resources as oil, gas, and coal. It should be noted that wind energy does not pollute the environment and is capable of producing pure, inexhaustible energy in a local area.

Sail wind-driven motors possess a unique feature — they operate equally well at small wind velocities as at large ones due to the fact that the shape of the working surface varies dynamically under the action of wind.

The construction of actual wind-driven plants requires knowledge of such aerodynamic characteristics as the drag coefficient and thrust force depending on the geometric parameters and operating conditions. The aim of the present work is the experimental investigation of the drag of sail blades of dynamically variable shape.

A survey of previous works has shown that the available data [1–3] are not always consistent, whereas there are practically no experimental values of the aerodynamic characteristics of sail blades for small velocities. In the works of Hoffman [4] the results of mathematical simulation of the sail are given, but without comparison with experimental data.

Experimental Wind-Driven Turbine Plant and Investigation Technique. We have developed a sail-type wind-driven turbine with blades of triangular shape made in the form of a flexible triangular sail with a mobile end. The schematic diagram of such a wind turbine is presented in Fig. 1. The wind turbine operates as follows: under the action of a wind flow the triangular wind turbine blade located at an angle to the wind direction experiences the side pressure force, and, according to the laws of aerodynamics, pushes the framework, setting it into rotational motion. The appearing force is the thrust force of the blade that transforms the wind energy into the rotational motion of the wind turbine. When the wind changes its direction, the direction of rotation of the axis of the authors′ wind turbine does not change (Fig. 2). As shown in Fig. 2, blade 1 with a dynamically varying shape of the surface made in the form of a triangular "sail" with a mobile end is thrown over to the opposite side of the rotating framework of the wind turbine on change in the wind direction, thus retaining the initial direction of turbine axis rotation. The wind turbine retains the capacity for work in a wide range of wind directions.

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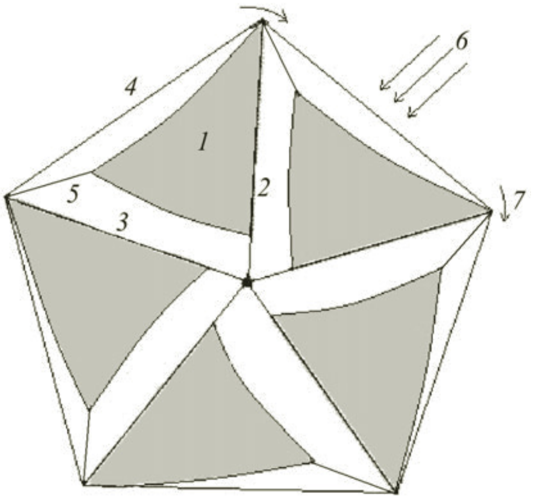

Fig. 1. Scheme of operation of a wind turbine with a dynamically varying shape of the surface of blades: 1) blade of the wind turbine with a dynamically varying shape; 2, 3, 4) elements of the framework; 5) regulated felxible attachement of the mobile end of the blade made from a strength thread; 6) direction of wind; 7) direction of turbine rotation.

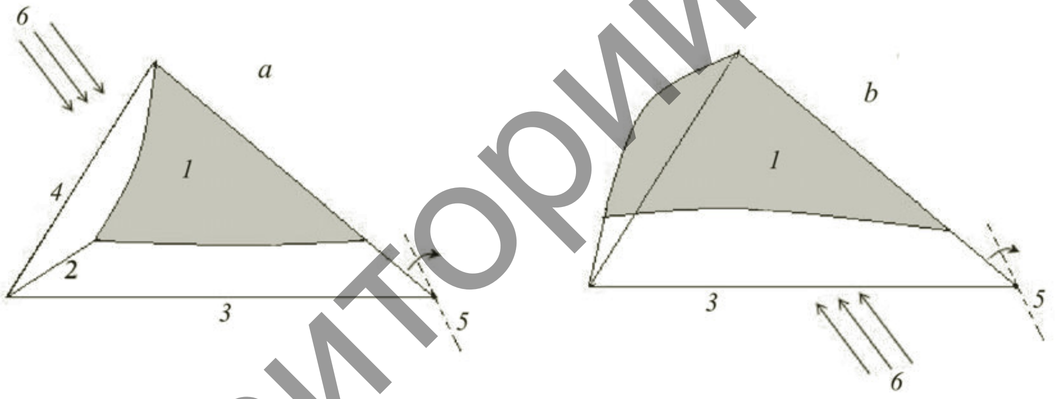

Fig. 2. Scheme of operation of the wind turbine blade in the case of straight (a) and reverse (b) direction of wind: 1) wind turbine blade; 2) flexible fixture of the mobile end of the blade from a kapron (parachute) thread; 3, 4) rods of the wind turbine framework; 5) rotation axis, the bent narrow shows the direction of the wind turbine axis rotation; 6) direction of wind.

The proposed wind turbine exhibits optimal aerodynamic characteristics due to the self-regulated shape of the blade surface during rotation under the action of direct and radial wind flows. The wind turbine in a wind flow is a self-organized facility that efficiently transforms the wind energy into the energy of rotational motion. The flexibility of the construction is ensured on account of the minimum magnitude of aerodynamic drag, which leads to an increase in the wind utilization factor.

There exists the possibility of sustaining a constant number of wind turbine rotations by varying the length of fastening threads of the mobile ends of blades in wind velocity ranges.

We consider unsteady turbulent air flow past a sail blade of a wind turbine. The experimental model (Fig. 3) consists of a wind wheel made from metallic framework rods; six sail blades of triangular shape made from a light and strength material (silk) one end of which is attached to the framework apex by a strong thread; supporting rods, and a bearing with an inner diameter of 8 mm. The model is fixed on a pillar by the supporting rods. The diameter of the sail wheel is 400 mm. With the aid of a pulley and belt transmission, the model of the sail wind-driven motor is connected with a low-power generator for producing electric energy [5].

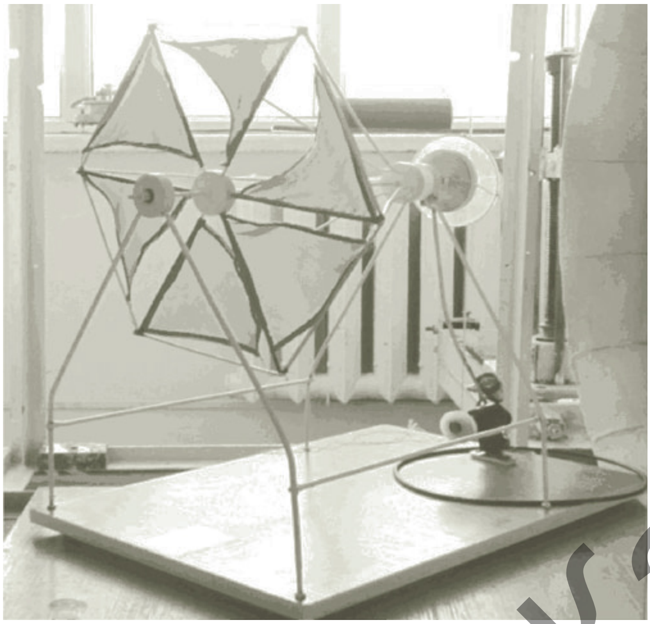

Fig. 3. Experimental model of a wind turbine with a dynamically varying shape of the blade surface.

Under laboratory conditions we carried out investigations to determine the aerodynamic characteristics of wind turbine blades with a dynamically varying shape of the surface. All tests were carried out in a T-1-M wind tunnel (Fig. 4). The main characteristics of the working part of the wind tunnel are: diameter 50 cm, length 80 cm, turbulence level 3%, and flow velocity 1–25 m/s.

The dimensionless drag coefficient C_x, lift coefficient C_y, and the similarity number (Reynolds number) were determined by the following formulas:

$$C_x = \frac{2F_x}{\rho u^2 S}, \quad C_y = \frac{2F_y}{\rho u^2 S}, \quad \mathrm{Re} = \frac{uL}{\nu}.$$

The drag and lift forces were measured with the aid of a three-component aerodynamic balance. A specimen of the sail blade of the wind turbine was placed in an air flow of given velocity on the balance frame with the aid of suspensions (Fig. 4). The horizontal forces that specify the drag force are transferred with the aid of tension members to the first balance and are recorded by it. The vertical forces that in sum determine the lift force are fixed by the second and third balances (not shown in the figure). The main area of the triangular sail and, consequently, the load are concentrated in the lower third of the sail [7–11].

Discussion of Results. To assess the efficiency of wind energy transformation into the energy of rotational motion, we carried out investigations to determine the aerodynamic characteristics of one blade of the experimental model made in the form of a triangular "sail" with a mobile end.

Figure 5 presents the dependence of the drag coefficient of the wind turbine sail blade β on the dimensionless angle of attack of the flow α for a wind velocity of 5 m/s. As the nondimensionalizing angular parameter we used the characteristic angle of 90° on the passage of which the "belly" of the blade sail is thrown over to the opposite side:

$$\beta = \frac{\alpha}{90^{\circ}}.$$

The decrease in the drag coefficient with increase in the angle of attack can be explained as follows: at an angle of attack of 0° the mid-section area of the wind wheel in relation to the circumfluent wind flow is maximum. Correspondingly, the wind wheel in such a position will possess a maximum force of resistance to the wind flow. With increase in the angle of attack, the wind wheel will alter its angular position relative to the wind flow. The change in the angular position is accompanied by a decrease in the mid-section area of the wind wheel relative to the incident flow, which leads to a decrease in the drag force and, correspondingly, to a decrease in the drag coefficient.

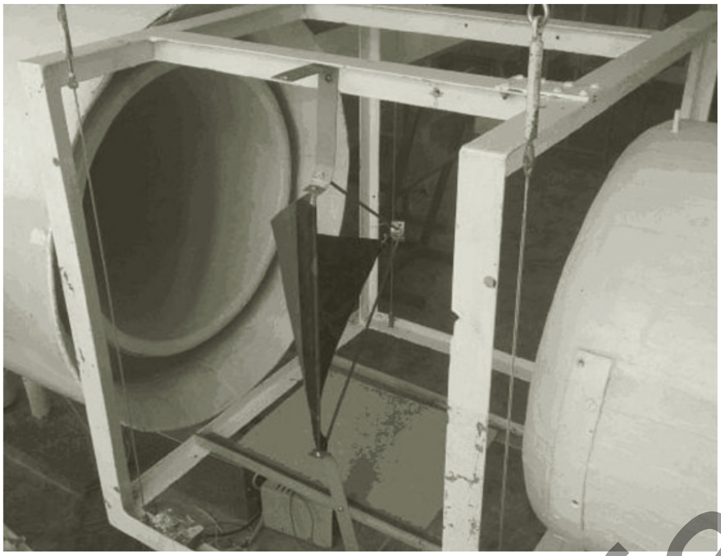

Fig. 4. Location of the blade in a T-1-M wind tunnel.

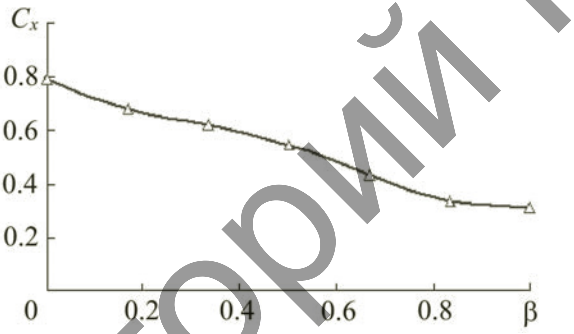

Fig. 5. Drag ressitance of the sail blade of a wind turbine vs. the dimensionless angle of attack at a wind velocity of 5 m/s.

Figure 6 shows the dependence of the lift coefficient of the wind-turbine sail blade on the dimensionless angle of attack of the flow at a wind velocity of 5 m/s. The peak of the curve in Fig. 6 is attributable to the fact that at the angle of attack of 0^{o} to the blade the fullness of the sail "belly" is equal to zero, whereas with increase in the angle of attack up to 15^{o} the sail is sagged, the pressure of flow on the sail blade surface increases, and the lift coefficient increases correspondingly. On further increase in the angle of attack, the area of the streamlined sail blade will decrease, which will be accompanied by a decrease in the lift force.

The aerodynamic qualities of the sail are characterized by a polar diagram, i.e., the graph of the change in the lift force depending on the drag and angle of attack. Since the polar diagram could be applied to sail of any dimension, we lay off not the value of forces along the coordinate axes, but rather the dimensionless lift coefficients of sails in a wind tunnel [12, 13].

Figure 7 presents polar diagrams of a sail blade for a wind velocity of 5 m/s. The forms of the obtained polar diagrams (Fig. 7) virtually coincide with the polar diagrams presented in [14]. The drag coefficient for our case is higher than for a rigidly fixed sail because our sail blade is regulated by the flexibly attached mobile end of the blade that thus ensures a dynamically varying surface of the blade.

We have obtained the dependences of the lift (Fig. 8) and drag (Fig. 9) coefficients on the number of blades. It is seen from Fig. 8 that the lift coefficient increases substantially with the number of blades at a constant area of the wind wheel, constant wind velocity, and a constant angle of attack. Figure 9 shows that up to $n = 6$ the value of the drag coefficient increases slowly and then remains constant. A further increase in the number of blades is inexpedient, since it increases the

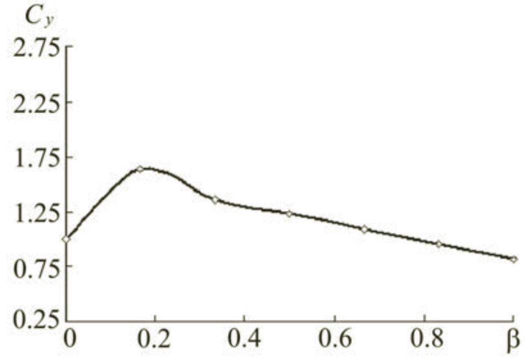

Fig. 6. The lift coefficient of a sail blade of a wind turbine vs. the dimensionless angle of attack at a wind velocity of 5 m/s.

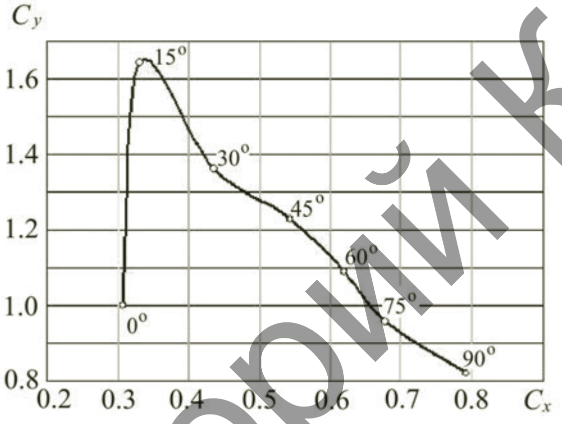

Fig. 7. Polar diagrams of a sail blade at a wind velocity of 5 m/s.

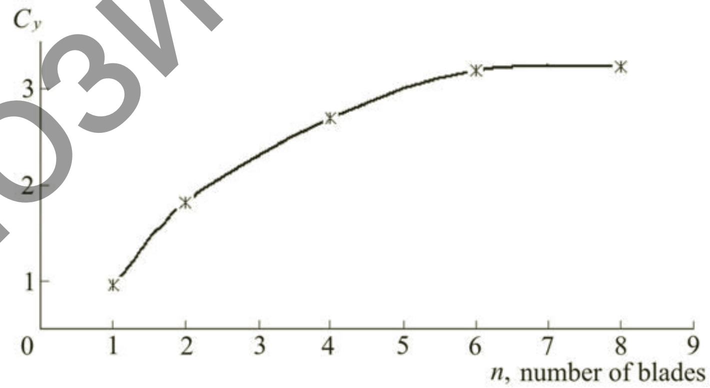

Fig. 8. Lift force vs. the number of blades.

amount of needed metal and the cost of the wind turbine. Thus, it has been determined that for a wind turbine with blades of dynamically varying shape the optimal number of blades is 6.

In comparison of sail wind turbines with multiblade wind turbines it is seen that the values of the minimum velocity (start-up velocity) of wind at which wind turbines start to operate differ by two times: 2.5–4 m/s for multiblade turbines and 0.5–1.5 m/s for sail turbines [13–15]. The difference in the characteristic is mainly determined by the "fullness" of the circle

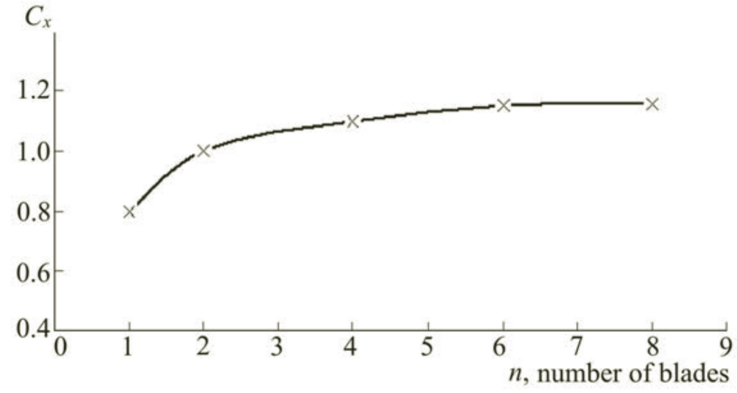

Fig. 9. Drag coefficient vs. the number of blades.

described by the blades: the fuller the circle, the lower the working wind velocity. Sail-type wind turbines produce energy even at low wind velocities (below 3 m/s).

Thus, the advantages of the sail wind turbines are:

1) minimum wind velocity at the start (0.5–1.5 m/s);

2) the sail is virtually instantly adjusted to the force and direction of wind, which ensures the operation of a sail wind turbine in a wide range of wind velocities, from the smallest ones to those typical of storms (50–60 m/s);

3) the sail is a light blade of large area that allows one to "take" energy with the least inertia from a minimum wind;

4) the sail is cheaper and lighter than the blade, which simplifies repairs and increases the maintenance utility;

5) the availability of the material for fabrication of blades (sail cloth, parachute silk, etc.) in contrast to composite glass plastics, special alloys, and blade–and blade honeycombs of vertical wind turbines;

6) sail blades can easily be transported;

7) sail wind turbines can be vertical or horizontal;

8) sail wind turbines do not produce noise infrasound and radio interferences (the sails are radio transparent [13–15].

Conclusions. In the present article we consider the characteristic features of operation of a wind turbine with blades in the form of sails. We carried out experiments with the use of a T-1-M wind tunnel. As a result of investigation of the streamlining of a sail blade, we obtained the dependences of the drag and lift coefficients on the dimensionless angle of attack. Based on the experimental data obtained, we constructed a polar diagram of the sail blade, which is the characteristic of the aerodynamic quality of the sail.

It has been established that the optimum number of blades for a wind turbine with a dynamically varying shape of the surface is $n = 6$. A further increase in the number of blades leads to an increase in the amount of needed metal for the wind turbine structure, with the aerodynamic efficiency of wind turbine operation remaining intact.

Limitations for a real sail blade as to its strength characteristics are determined from the velocity of wind bursts. Real constructions of a wind turbine are calculated for its safe operation up to a wind velocity of 15–17 m/s. At a wind velocity above 25 m/s a storm guard is triggered and the sails are rolled up into a "pipe." The Reynolds number for the real characteristic size of a sail of about 2 m is

$$\mathrm{Re} = \frac{2\ \mathrm{m} \cdot 17\ \mathrm{m/s}}{1.5 \cdot 10^{-5}\ \mathrm{m}^2/\mathrm{s}} \approx 2.26 \cdot 10^{6} \ .$$

The results obtained will be of use in the construction of a pilot specimen of a wind turbine, and the numerical data can be used by specialists in research in the field of aerodynamics.

NOTATION

F_x, drag force, N; F_y, lift force, N; L, characteristic dimension of the sail [6], m; u, flow velocity, m/s; S, mid-section area, m^2; ρ, air density, kg/m^3; ν, kinematic viscosity of air, m^2/s.

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