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COMPARATIVE STUDY OF AERODYNAMIC CHARACTERISTICS OF VARIOUS SAIL TYPE WIND TURBINES

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The article presents the results of experiments on the study of aerodynamic characteristics of various models of sail-type wind turbines under different flow conditions. The description of procedure of testing and measurement of aerodynamic forces is presented. The authors obtained thrust and drag forces graphs at different rates and angles of attack of the air flow. They defined the dependence of head drag and thrust forces coefficients when Reynolds number changed. The results of the comparative analysis of the aerodynamic characteristics of three models of sail-type wind turbine are presented.

Keywords: aerodynamics, sail type wind turbine, drag force, traction force, angle of attack.

Introduction

Despite the fairly large hydrocarbon resources, at the present stage one of the main tasks of the dynamic development of Kazakhstan's economy is the effective and efficient use of renewable energy sources (RES). The urgency and importance of this issue is confirmed by domestic and foreign scientific publications, technical innovations and developments, and long-term state Programs [1-5]. For example, [5] gives a complete overview and analysis of the current state of energy consumption in Kazakhstan and possibilities of using renewable energy sources from the standpoint of technology and economy. Principal barriers to the development and use of renewable energy resources in Kazakhstan are considered. Legislative economic and investment instruments to support renewable energy sector are offered. Indeed, so far no greater than 1% of total energy consumption is produced by means of renewable energy resources.

Thanks to a sufficiently large territory of Kazakhstan and the appropriate wind energy resources, wind power is the most available for use of all types of renewable energy resources [6]. Creation of low-power wind turbines is necessary and essential to provide electricity to small farms, far from centralized power lines. Moreover, consumers of the first category of reliability of power supply (border observation systems, retransmitters, mobile communication and telecommunication systems,) are in particular need of local energy resources to use. Currently, about 170 MW is required to meet the energy deficit of remote objects in Kazakhstan [3, 4].

Kazakhstan has already begun work on the construction of wind farms. Despite the fact that now the share of renewable energy resources in total electricity production is only 0.5%, by 2020 this indicator should reach 3% [1]. Low-power wind turbines can provide power supply to regions with an average wind speed (3-5) m/s. In fact, an owner of a small wind turbine becomes almost completely independent from both the traditional energy producers as well as from natural phenomena [6].

This paper presents the results of the analysis of experimental data on the study of aerodynamics of three different models of sail-type wind turbines: two of them with different numbers of sail blades and the combined model with two wind wheels, the plane of rotation of which are arranged perpendicular to each other.

The study of aerodynamics characteristics and the choice of sail-type wind turbines are due to the fact that they have a relatively low starting speed and are able to transform the wind energy at speeds less than 3 m/s, at which vane-type turbines are still [7-10]. Furthermore, a sail-type wind turbine is easily adjusted to the direction of the wind, hardly makes noise and vibration.

Measurement technique

As part of these studies several models of sail-type wind turbines were made. They were: wind turbines with different numbers of sail blades (6 and 8), as well as twinned (coupled) combined model with two 6-bladed wind wheels set perpendicular to each other (Table 1); the detailed description and schemes of models are presented in [11-15]. The major distinction of the developed models of sail-type wind turbines from other well-known ones is that two ends of triangular shaped sail blades made of durable water-repellent fabric are firmly fixed to the frame of the wind wheel, and the rest end is loosely fastened to the top of the frame with a cord. Experiments have shown that it provides flexibility to sail blade surface shape and its self-regulation at straight and radial flow, whereby the wind turbine may effectively convert energy of air flow into the energy of rotational motion. As shown by the experiments, the direction of rotation of the wind wheel with such sail blades lashing does not change even when the air flow changes in the opposite direction [11, 14].

Table 1. Parameters of the sail type wind turbine models

Description of models	Designation	Mass of models, kg	Diameter of wind wheels d_s, m
Model with six sail blades	6s	1,2	0,4
Model with eight sail blades	8s	1,4	0,4
Twinned (coupled) combined model with two 6-bladed wind wheels	Ds	1,8	0,32

Experiments to determine the aerodynamic characteristics of models of sail-type wind turbines were carried out at a big wind tunnel T-I-M with an open test section, [14, 15]. Parameters of the working section: the diameter Dt is 0.5 m, the length Lt is 0.8 m. The experiments in the wind tunnel are based on the principle of reversibility of motion, according to which displacement of a body with respect to the air can be replaced by air motion incoming to a motionless body. In the working part, an air flow is formed with a uniform rate field within the range from 3 m/s to 25 m/s, the turbulence level of 3%.

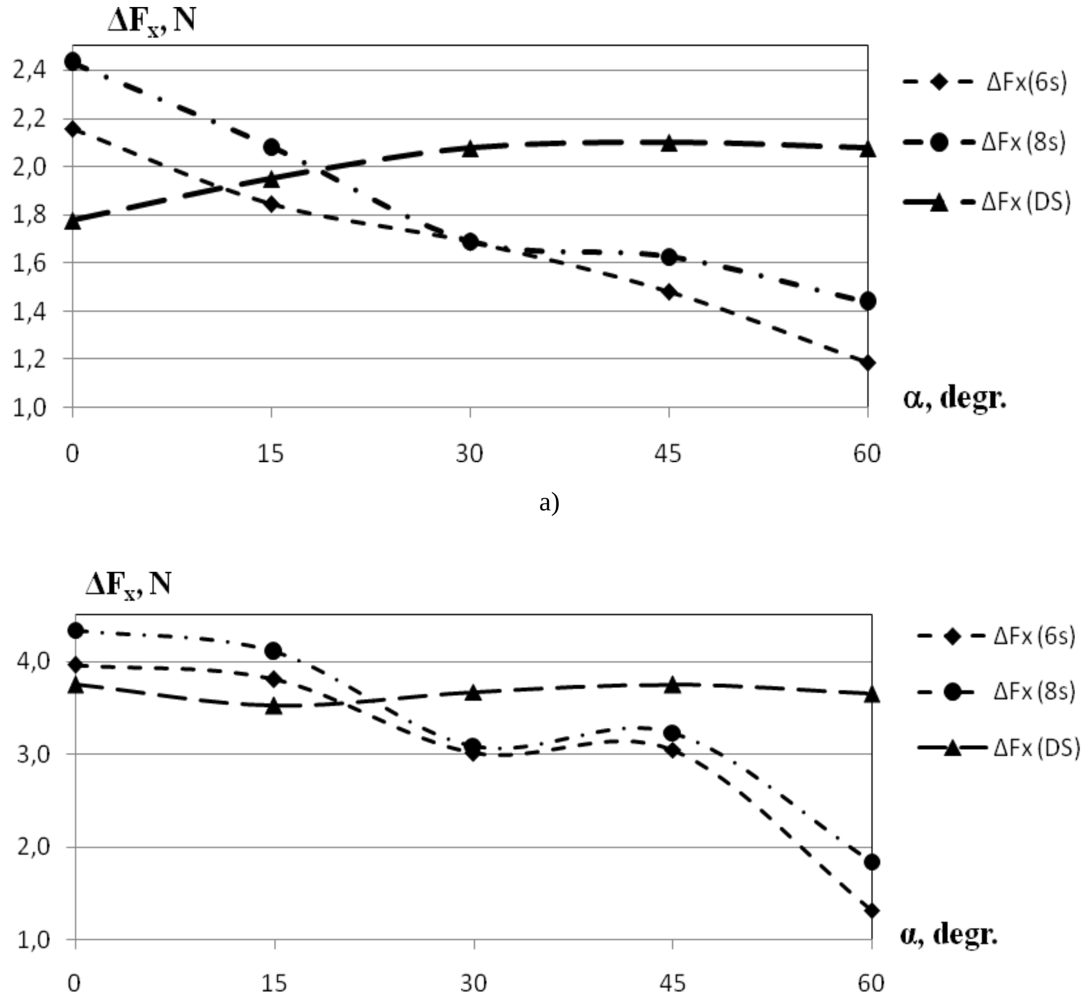
In the experiments, a three-component mechanical aerodynamic balance was used to measure the components of aerodynamic forces and moments acting on the model. The aerodynamic balance is attached to a rigid cubic frame through special-purpose tailings. The studied wind turbine model is placed in the frame. The flow of air coming to the frontal part of the model provides the force, so that the balance indicator deviates from equilibrium. The cubic frame provides independent measurements of aerodynamic forces in different directions. This makes possible to measure the value of the lift force F_y and drag force F_x. Using a special device the wind wheel plane of the model turns by a predetermined α angle with respect to the direction of air flow, thus providing flow-around at different α attack angles (yaw angles).

Using dynamometers, attached to the sheave, the traction force F_t at different parameters of the air flow was measured. The traction force is regarded as a positive effect when converting flow energy into the energy of the rotational motion of the wind wheel. All measurements were repeated at least (3-5) times, the measurement accuracy of aerodynamic forces does not exceed 4%.

Experimental results and discussion

As the result of the tests, dependence graphs of some aerodynamic characteristics of various models of wind turbines at various speeds and angles of attack of the air flow were obtained. Figures 1 and 2 show the dependences of the change in drag and thrust forces for three different models of sail-type wind turbine on the angle of attack at two flow rates of 5 m/s and 7 m/s.

The vertical axis in Figure 1 shows changes in the values of aerodynamic balance readings, i.e., difference between a drag force without air flow F_{x0} and the one with the latter F_x : $\Delta F_x = F_x - F_{x0}$.



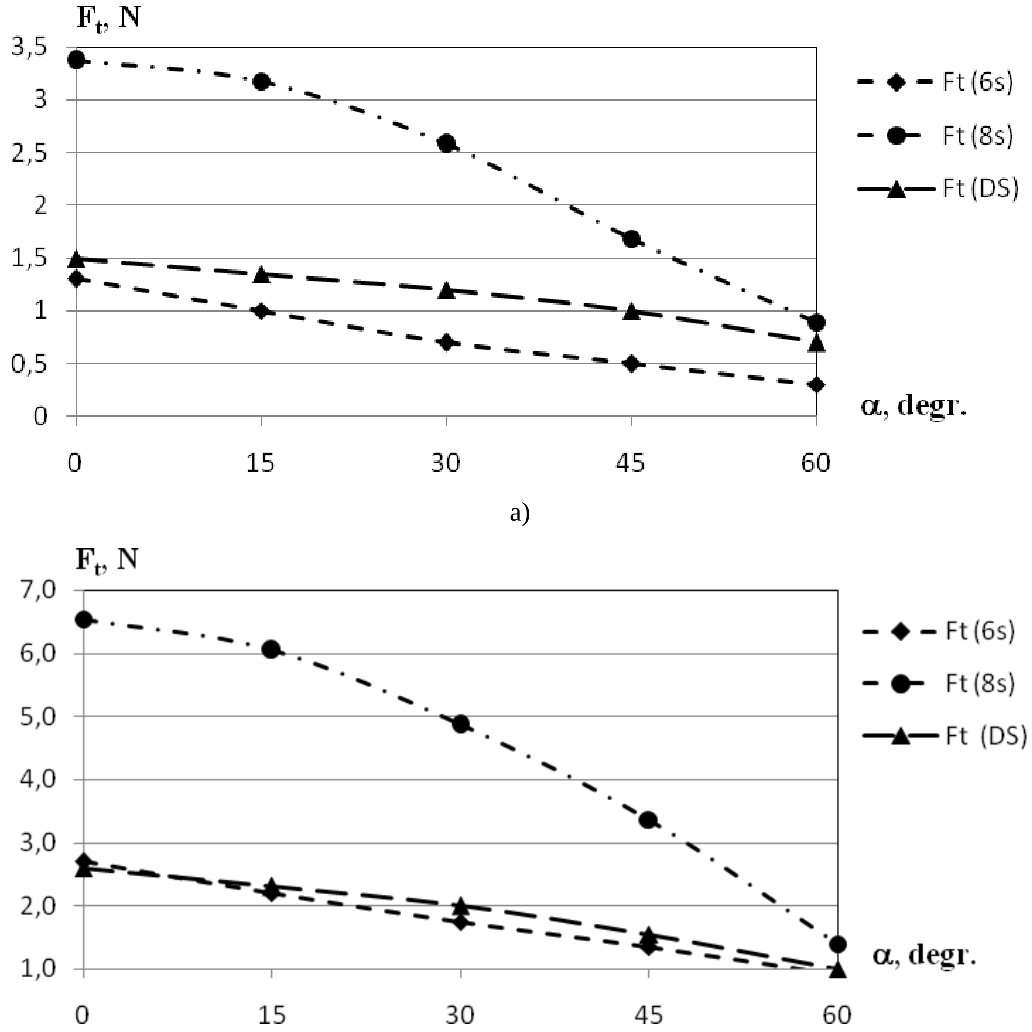
a)

b)

Fig.1. The dependence of drag forces of three sail-type wind turbine models on the angle of attack at a flow rate of: a) 5 m/s; b) 7m/s

These graphs (Fig.1) show that with the increase in the flow yaw angle, the drag force changes in different ways: for two models with one wind wheel it reduces and for coupled wind turbine model it virtually hardly changes and slightly increases. The reasons of these facts are the following. In the case of one wind wheel models, the more the angle of attack, the less the flown mid-section area, on which the air flow exerts a force. This is not in the case of the flow past the model of the coupled wind turbine. On the contrary, here the drag force increases, since when the angle of attack of the flow grows, the swirl of the air flow is increased by two wind wheels. The interaction of the latter creates a kind of additional diffusion.

The graphs in Figure 2 show that the increase in the angle of attack leads to reduction in the value of thrust force of all models of sail-type wind turbines for two values of air flow rate. The greatest rate of decrease in the value of thrust force is observed for the 8-blade model. Within this range of the flow yaw angles, its value reduces by more than 2 times. The least rate of reduction in the value of thrust force is observed for the coupled wind turbines model. In this case, a decrease in the values of thrust force by 30% can be seen.



a)

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Fig.2. The dependence of the thrust force of the three models of sail-type wind turbines on the angle of attack at the wind speed: a) 5 m/s; b) 7m/s

In addition, it was found that this model of the coupled wind turbine is more efficient when the direction of the incoming air flow changes because, despite the increase in the yaw angle of the flow, both wind wheels cover a sufficiently large volume of air flow as if complementing each other.

In the course of experiments the authors also studied dependencies of change in the values of drag force and thrust forces on change in the yaw angle of the flow at higher air flow rates: at 9 m/s and 11m/s. Analysis of the results showed similar dependences of these forces on the yaw angle of the flow for all models.

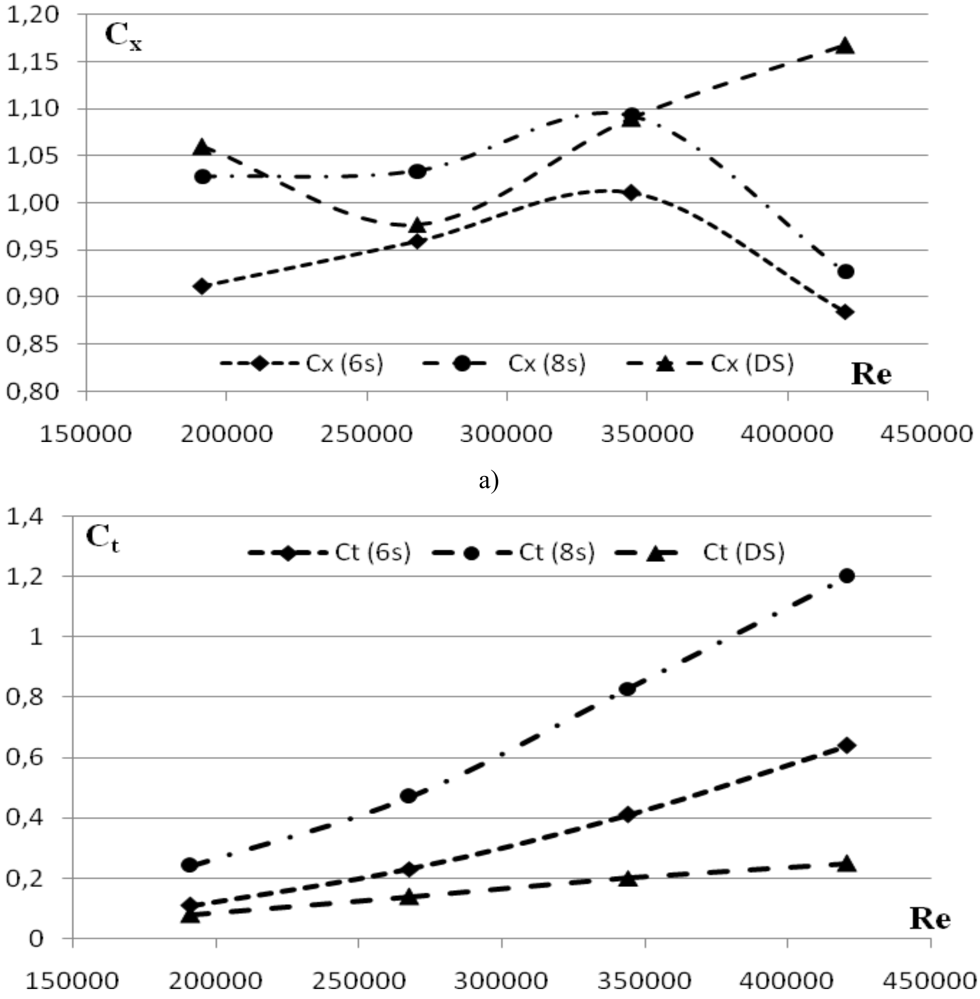
To determine the universal dependence of the studied models, the experimenters determined values of dimensionless aerodynamic characteristics under different flow conditions using relationships generally accepted in aerodynamic calculations [16, 17].

Figure 3 shows dependence graphs of aerodynamic coefficients on the airflow rate at a 0° angle of attack in the dimensionless form for the three considered models: drag coefficient C_x and thrust coefficient C_t.

The drag coefficient C_x was calculated according to the formula:

$$C_x = \frac{\Delta F_x}{\frac{\rho \cdot u^2}{2} \cdot S}$$

where ρ is air density, u is the airflow rate, S is the area of the sail wind wheel.



a)

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Fig. 3. The dependence of dimensionless aerodynamic characteristics on the airflow rate at angles of attack of 0°: a) drag coefficient; b) thrust coefficient.

The horizontal axis OX shows the airflow rate in the dimensionless form, i.e.

$$Re = \frac{u \cdot D}{\nu},$$

where ν is the kinematic viscosity coefficient of air, u is the airflow rate, D is the diameter of the working part of the wind tunnel, D=0.5 m.

In calculations, the values of the parameters of air at a temperature t=20°C and the pressure of P=105Pa are accepted: $\rho = 1{,}29\ kg/m^2 \rho = 1{,}29\ kg/m^2$, $\nu = 13{,}07 \cdot 10^{-6} m^2/s$.

The area of the wind wheel, flown by the airflow for one wind wheel 6- and 8-blade models of the same diameter d_s = 0.4 m is equal to $S = \pi \cdot d_s^2/4$ = 0.13 m^2. For the model of the coupled wind turbine with two wind wheels having the diameter d_{Ds} = 0.32 m, set at an angle of 45° to the direction of the airflow the area is calculated as follows: $S = 2 \cdot \pi \cdot \sin 45° \cdot d_{Ds}^2/4$ = 0.11 m^2.

The thrust coefficient is defined by the ratio of thrust and gravity forces of the model: $C_t = \frac{F_t}{mg}$

It is known that at the flow past bodies at high Reynolds numbers (of the order of thousands) the viscous forces can be neglected in comparison with the forces of the vortex origin which, however, indirectly occur due to friction. Within this range of Reynolds numbers, there are quite different patterns of change in drag coefficient C_x for all models, which probably can be attributed to the additional flow turbulence owing to the sail blades.

When of bodies of classical form, such as sphere, cylinder are flown in a certain area of Reynolds numbers (for the ball within the range from 200000 to 300000, for a cylinder - from 400000 to 500000), there suddenly occurs a sharp decrease in drag coefficient. The drag coefficient can reduce by three or more times, and then at a further increase in the Reynolds number, it again remains almost constant [16, 17]. This phenomenon is called a crisis and is due to the process accompanying shedding of vortices.

As can be seen from Fig.3a, an increase followed by a decrease in the drag coefficient is observed for 6-and 8-bladed models. As to the doubled model, just after the decrease in the value of drag coefficient, on the contrary, it increases. This owes to the additional flow turbulence thanks to the design features of the model.

In Figure 3b in graphs for all models an increase in the thrust coefficient can be seen when the incoming air flow increases at an angle of 0º, which corresponds to the perpendicular flow direction to the surface of the wind wheel.

In the case of a coupled, combined model, the air flow is directed actually to the middle of the model, i.e., at the angle of 45º to the surface of each wind wheel. But if the drag force increases virtually the same for all models, the thrust force increases faster for 8-blade wind turbine that confirms its effectiveness when airflow rate grows.

Conclusion

A series of experiments was made to determine the aerodynamic characteristics of various models of sail-type wind turbines with a dynamically variable shape of blade surface. Dependence graphs of drag force on the rate and direction of the airflow are obtained, they correspond to the physical flow pattern. Indeed, when the airflow rate grows, the value of the drag force of the wind turbine rises. It is due to the increase in pressure acting on the surface of the wind wheel frame and sail blades. And conversely, that owes to the fall in the pressure force of the air flow when the angle of attack rises thanks to the reduction in the flown surface area.

If we compare the patterns of models with one wind wheel, then the 8-blade one is more effective, since at an increase in the air flow rate, the drag force rises more slowly, and the thrust force grows much faster than that of the 6-blade wind wheel. But when the direction of the airflow changes, these characteristics decrease faster. It was established experimentally that the model of a coupled sail-type wind turbine with two wind wheels more effectively converts the energy of the incoming airflow while changing its direction.

It should be noted that the above mentioned patterns of drag and thrust force change are obtained for these models under these conditions in the experimental tests. In practice it is necessary to consider the influence of other parameters, such as temperature, degree of atmospheric humidity.

The applied results can be used in engineering analysis in the development of multiblade sail-type wind-driven power plants, adapted to the specific climatic conditions, operating at low wind speeds and generating a demanded amount of electric energy.

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