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A SAIL-TYPE WINDTURBINE FOR LOW-SPEED WIND

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The article gives a brief overview of the most significant results obtained during the execution of the grant project (state registration number 0113RK01001). Within the framework of the project the investigators studied possibility of using low-speed wind energy in the city of Karaganda. They developed and created a variety of models of low power sail-type multiblade wind turbine to convert wind energy. The originality of the presented wind turbine is that blades with a dynamically variable surface shape are used. The analysis of results of aerodynamic testing of wind turbine models was performed at a laboratory-scale plant and in natural wind under different climatic conditions.

Keywords: aerodynamics, sail type wind turbine, sail with a dynamically variable surface shape, thrust force, angle of attack, wind-driven power plant

Introduction

One of the most important features of the development at the present stage is the increased attention of the world community to the problems of rational and efficient use of energy resources, implementation of energy saving technologies and search for renewable energy sources. The increase in humanity's demand for energy resources makes search and greater use of alternative power supply sources necessary. First among them is wind power engineering. For its development it is extremely important to be armed with reliable information on the wind regime in the territory of the expected position of wind-driven power plants. On account of the large territory of the country, the potential of renewable energy resources (hydro-energy, wind and solar energy) is very significant in Kazakhstan. But until now, the percentage of the use of alternative energy in the republic is only 0.4% of the total [1-3]. One of the reasons of under exploitation of the huge reserve of wind energy is the lack of efficient wind turbines for low speed winds typical for the greater part of the territory of the Republic of Kazakhstan.

In this regard, the construction of small wind-driven power plants effectively working under conditions of low average annual wind speed is very topical for Kazakhstan, and it falls into line with the priorities of science development in the country. This problem in our republic has become particularly relevant in connection with the preparation of Kazakhstan to the World Exhibition of Science and Technology "EXPO-2017"[2-4]. The main thematic trends of «EXPO-2017» are the concepts of "Energy of the Future" and "Environmentally Friendly Power Generation".

1. Formulation of the problem

The increased interest in wind-driven power plants causes the urgency of the problem of aerodynamic optimization of wind engines. The development of WDPP that meets specific technical requirements is carried out through the search of a large number of geometric shapes of wind-driven devices, with an estimate of their aerodynamic parameters. Calculation of aerodynamic characteristics of wind engines and aerodynamic tests make it possible to analyze the characteristics of wind machines and appreciate advantages under changing flow conditions.

Sail wind engines have a unique feature – they operate equally effective both at low and high speed wind owing to dynamically changeable shape of the working surface under the influence of the wind flow. The main idea is the efficient use of energy of ground winds of low speed using multiblade wind engines with dynamically variable shape of blades, made in the form of a triangular "sail" with a movable end.

Close analogues of wind engines designed to operate at low average annual wind speed are described in works of N.M. Bychkov (IAM, Novosibirsk) [5-6] and N. Murakami (Japan) [7,8]. There a wind engine for low wind speed on the basis of the Magnus effect is described. The closest analogue of the sail-type wind engine is described in the papers of B.V. Wojciechowski, performed at Lavrentiev Institute of Hydrodynamics SB RAS. (IHD, Novosibirsk) [9]. The disadvantage of this multiblade wind turbine is the impossibility to optimize the aerodynamic characteristics of the wind engine during operation. Furthermore, a reverse change in the direction of the wind results in a reverse in the rotational direction of the wind wheel, which leads to unhandiness.

The objective is to develop and design low-powered multiblade wind engines for generation of electricity.

The novelty consists in the use of blades with a dynamically variable surface shape, made in the form of a triangular flexible sail with a movable end, as bearing elements of the wind turbine.

The setup and design as well as parameters of the developed wind turbine are described in detail in the works of the project authors [10-13]. The operating principle is that under the influence of wind flow a triangular blade inclined at an angle to the wind flow course experience a lateral pressure force and according to the laws of aerodynamics, it pushes the frame, causing its rotational motion. The emerging force is the thrust force of the blade that converts the wind energy into rotational motion of the wind turbine.

When the wind direction is reversed, the rotation direction of the wind turbine wind wheel is not changed. This is because when the wind direction changes, the blade in the form of a triangular "sail" with a movable end, is thrown to the other side of the rotating frame of the wind turbine, thus providing retention of the original direction of rotation of the wind wheel.

In the course of the study, the investigators developed and designed different models of low-powered sail-type multiblade wind turbines to convert wind energy. In order to determine the aerodynamic characteristics and to optimize the designed wind turbine, aerodynamic tests were carried out: in lab-scale T-1- M wind tunnel testing at various rates and angles of attack of airflow; in natural wind in different climatic seasons.

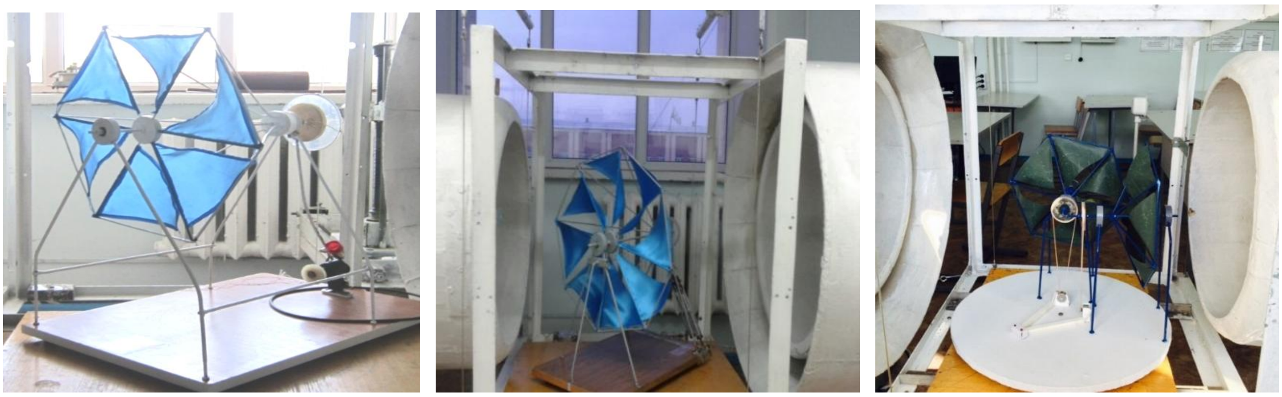
2. Laboratory tests in a wind tunnel T-M-1.

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, fig.1.

Parameters of the sail type wind turbine models are:

- model with six sail blades (6s) has a mass equal 1.2 kg, diameter of wind wheels d_s =0.4 m;
- model with eight sail blades (8s) has a mass equal 1.4 kg and the diameter of wind wheels d_s =0.4 m;
- twinned (coupled) combined model with two 6-bladed wind wheels (Ds) has a mass equal 1.8 kg, diameter of two wind wheels d_s =0.32 m.

The technique of laboratory tests in the wind tunnel T-I-M, its parameters and specifications of models are given in [14-17]. In the experiments, a three-component mechanical aerodynamic balance was used to measure the aerodynamic drag force F_x and moments acting on the model. 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 thrust force F_t at different parameters of the air flow was measured. The thrust 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%.



a) b) c)

Fig. 1. Models in wind tunnel T-M-1 working section: a) model with six sail blades;
b) model with eight sail blades; c) twinned (coupled) combined model with two wind wheels.

As the result of the tests, the dependences of the change in drag and thrust forces for three different models of sail-type wind turbine at various speeds and angles of attack of the air flow were obtained. It was obtained 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 [14].

To determine the universal dependence of the studied models it were determined values of dimensionless aerodynamic characteristics under different flow conditions using relationships generally accepted in aerodynamic calculations [15, 16].

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

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

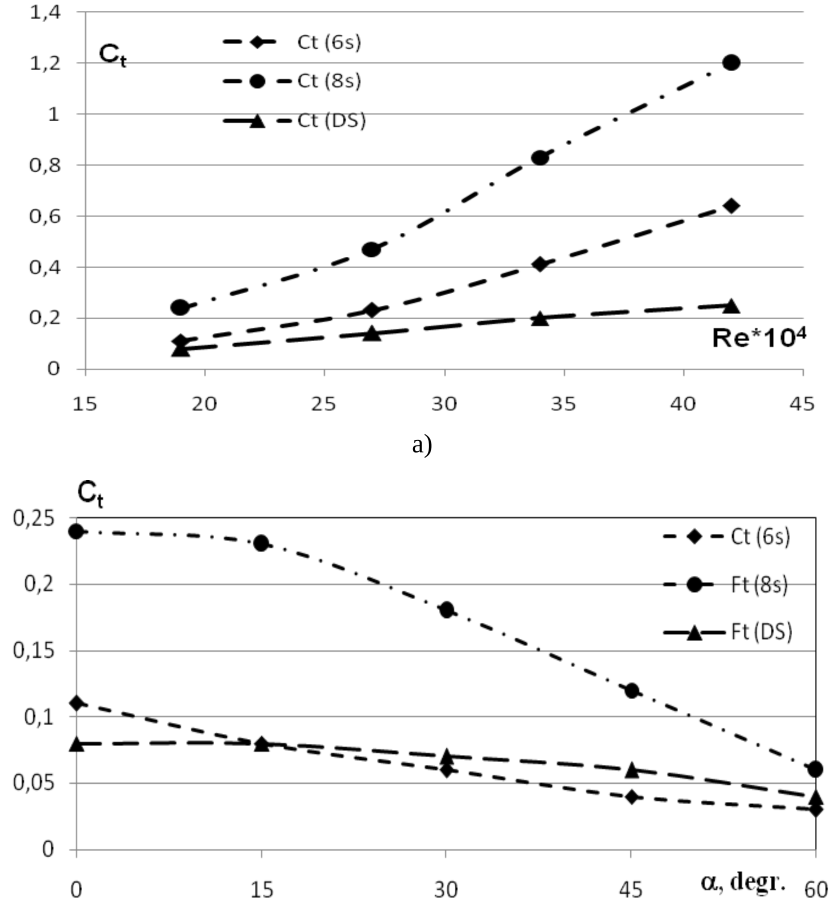
$$Re = \frac{u \cdot D}{\nu},$$

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: $\rho = 1{,}29\ kg/m^2 \rho = 1{,}29\ kg/m^2$, $\nu = 13{,}07 \cdot 10^{-6} m^2/s$.

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, fig.2. 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. The thrust force coefficient increases faster for 8-blade wind turbine that confirms its effectiveness when airflow rate grows, fig.2a.

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 [14]. The dependences of these forces on the yaw angle of the flow for all models are same at air flow rates from 3 m/s until 11m/s.



a)

b)

Fig. 2. The dependence of thrust coefficient:
a) on the airflow rate at α = 0º; b) on attack angles at the airflow velocity 5m/s.

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.

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 [10-14]. 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 [18].

3. Aerodynamic tests of WT-3 wind turbine under natural wind conditions

To carry out aerodynamic tests in natural wind, a prototype model of 6-blade sail-type wind turbine with the wind wheel diameter of 3 m was designed, Figure 3. The shaft of WT-3 wind turbine was made of a metal cylinder of 30 mm in diameter and 1750 mm in length. The diameter of the metal disc coaxially attached to the shaft was 150 mm; the disc thickness was 10 mm. The pulley with a diameter of 400 mm and a thickness of 40 mm was designed for the belt drive to the generator. The support bars and the frame rods of the wind wheel were metal tubes of 25 mm in diameter, fixed to the disc. The length of each frame rod of the wind turbine was 1570 mm and the length of the support bars of the wind wheel was 2100 mm. With a view to ensuring maximum thrust force of the sail blades 15 cm elongation of the movable yarn was selected. The prototype model of WT-3 wind machine was mounted at a height of 5 meters along the prevailing direction of the local wind flow. In addition, a solar panel was installed to provide electricity in windless weather.

The dependences of the thrust force on the speed at different wind directions; the values of the thrust force were defined by ordinary weighing method [10, 15]. The measurements showed that with an increase in wind speed, a growth of the thrust force of WT-3 wind turbine was observed. Thus, the wind turbine rapidly grew the thrust force. WT-3 wind turbine could operate at wind speed ranging between 3 m/s and 15 m/s. It was found that the maximum thrust force value was reached at a wind flow at attack angle $\alpha=0^0$ and the wind speed of 15 m/s.

Fig.3. The general view of the prototype model of WT-3 wind-driven power plant.

Figure 4 shows the dependence of the thrust coefficient of WT-3 wind turbine on the Reynolds number. It can be seen that at the direct and the reverse direction of the wind flow the values of the thrust coefficient vary slightly.

The experiments showed that the value of the thrust force lowered with increasing attack angle of the wind flow at constant wind speed. That was due to the reduction of the midship section area of the wind wheel. Figure 5 shows dependence graphs of thrust coefficient of WT-3 wind turbine on attack angle of the wind at two wind speeds. As a result of experimental tests the authors obtained dependences of the aerodynamic thrust force, thrust coefficient on the speed and attack angle of the wind flow. The thrust coefficient kept its serviceable value up to 45^0, and then with increasing attack angle of the wind flow it slowly lowered [10].

The key target when designing a wind engine is conversion of wind energy into electricity. In this connection, the investigators ran a number of field tests to determine the electro-physical parameters of WT-3 wind-driven power plant [19]. They examined volt-ampere characteristic of the prototype model of the wind-driven power plant at a fixed value of the pulley diameter. As a load for recording the volt-ampere characteristic of the wind-driven generator the experimenters used lamps with the power of 5 W and 21 W respectively

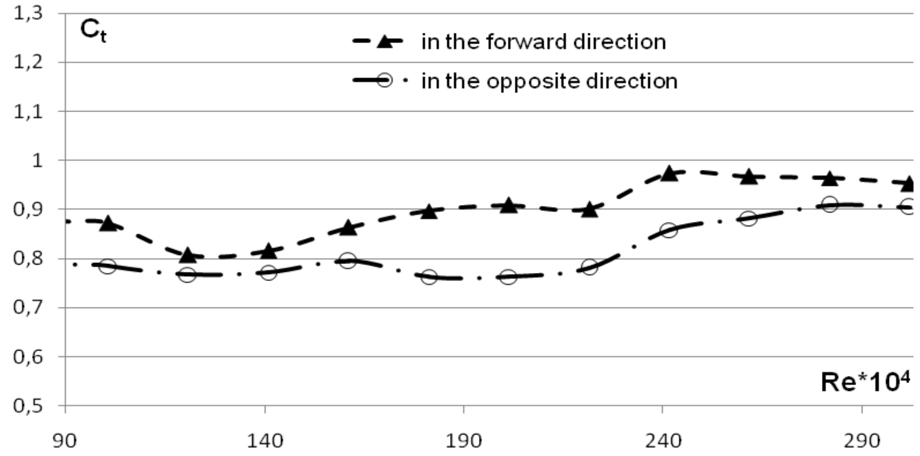


Fig.4. Dependence of the thrust force coefficient of the WT-3 on Reynolds number at different flow directions

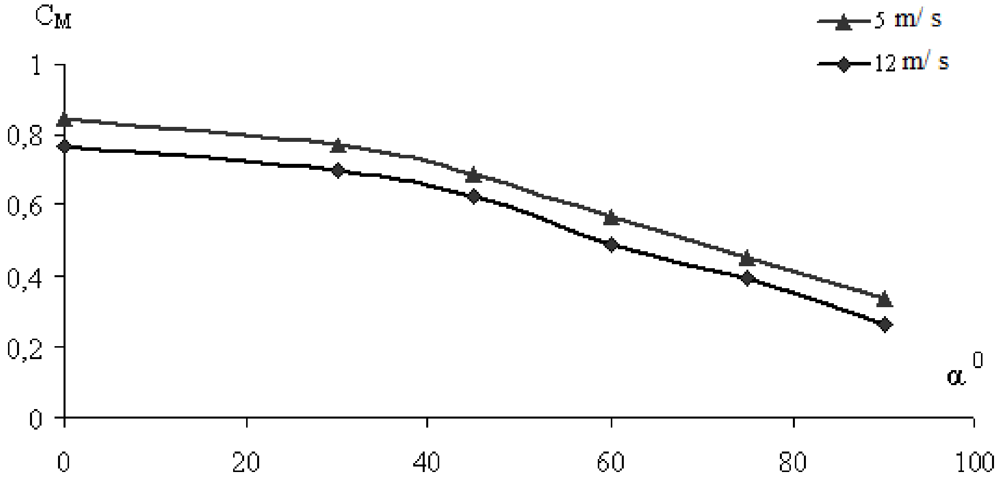


Fig. 5. Dependences of the thrust coefficient of WT-3 wind turbine on the attack angle of the wind flow.

It was found that the operating point of the generator connected to the load coincided with the maximum power point. Connection of such loads could shift the operating point of the system to a minimum or even zero power. Therefore, voltage converters that could match the wind-driven assembly unit with the load were important components of the system. The power of the wind-driven power plant, voltage, current and shaft speed depended on the wind speed, which transferred energy to the entire system.

Dependences of force and the voltage of generated current on the wind speed were studied. It was obvious that growing wind speed increased both rotation frequency of the wind wheel, and the values of generated voltage and current [19]. Figure 6 shows the dependence of the power of WT-3 wind-driven power plant in accordance with the measured voltage and current values on the wind speed. The power was calculated from the voltage and current by the formula: $W=U\times I$, where U is the generator output voltage, B; I is the current around the circuit, A. The generated power grows with increasing wind speed almost linearly; at wind speed of 7m/s WT-3 wind turbine generates the power of 330 watts. The maximum generating power at 12 m/s is 970 watts. The maximum rotation frequency of the wind wheel is 150 rev/min; the minimum threshold of operating wind speed is 3m/s; generated nominal power of WT-3 wind turbine is 1 kW [31].

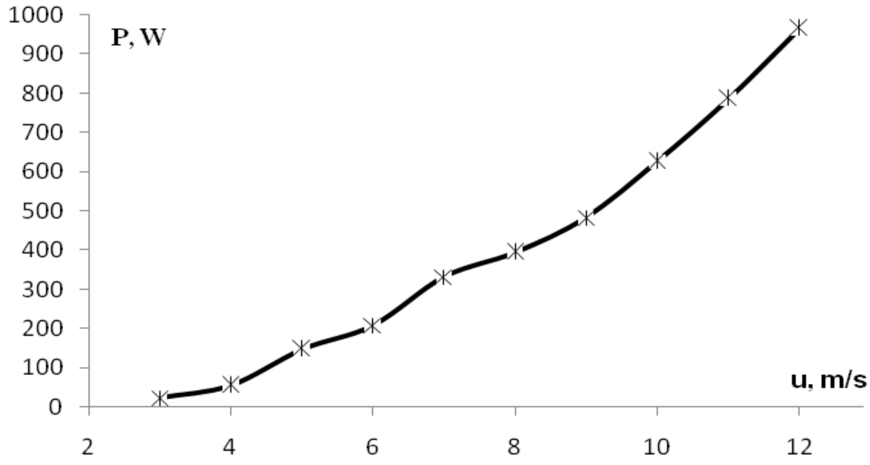


Fig. 6. Dependence of WT-3 wind turbine power on the wind speed.

The climate in Karaganda is sharply continental with cold winters, temperate hot summers and low annual rainfall. According to the meteorological station data for the Karaganda region in 2014, in the central part of Kazakhstan the annual average wind speed measured at a height of 10 m, was 3.8 m/s, and in Karaganda it was 3.2 m/s.

Through testing WT-3 wind turbine in natural wind, the experimenters determined aerodynamic characteristics depending on the wind speed and air temperature for each month [10]. They also studied the impact of air temperature on the value of the thrust force. They found that on warm days the work of the wind turbine depended only on the wind speed, and during the season of cold weather the operation efficiency of the wind turbine depended on the intensity of precipitation.

Based on the results of measurements, the investigators made up the Beaufort scale, characterizing the wind force, depending on its speed and its impact on the operation of WT-3 wind turbine [19, 21]. To avoid damage (sail disruption, breakage of frame rods and support bars) at high wind speeds, in the design of WT-3 wind turbine activation of storm proofing was provided. From the Beaufort scale, it followed that the optimum conditions for operation of wind-driven power plants with WT-3 wind turbine corresponded to wind speeds ranging between 3 and 12 m/s.

4. Aerodynamic field tests of WT- 4 wind turbine

Fig. 7 shows a general view of WT-4 wind turbine with the wind wheel diameter D=4 m. The shaft of 6-blade WT-4 wind turbine is a metallic cylinder with a diameter of 32 mm and a length of 2,330 mm. The diameter of the metal disc coaxially fastened to the shaft is 302 mm, the disc thickness is 16 mm. The pulley with a diameter of 400 mm and a thickness of 40 mm is designed for the belt drive to the generator. The support bars and the frame rods of the wind wheel are duralumin tubes with the diameter of 20 mm, fixed to the disk. The length of each frame rod of the wind turbine is 2,000 mm and the length of the support bars of the wind wheel is 2,429 mm. The rotation frequency of the wind wheel of the wind turbine is of 50-100 rev/min, the minimum threshold of operating wind speed is 3-5 m/s.

With a view to ensuring maximum thrust force of the sail blades 3-5 cm elongation of the movable yarn was selected. The axis of rotation of WT-4 wind turbine is located at a height of 3 m above the surface of the Earth; the total height is 5 m. Dependences of aerodynamic thrust force on the wind speed at its various directions were studied.

It was found that at forward flow of wind, the thrust force value is greater than at the reverse direction of the wind. This is because at the back of WT-4 wind turbine working parts are arranged, which create an extra obstacle for the wind flow and thereby block the rotation of the wind wheel.

a) b)

Fig.7. General view of WT-4 wind turbine: a) operational mode, b) - idle mode (sail blades are taken in)

Fig.8 shows a dependence graph of thrust coefficient of WT-4 wind turbine on the Reynolds number.

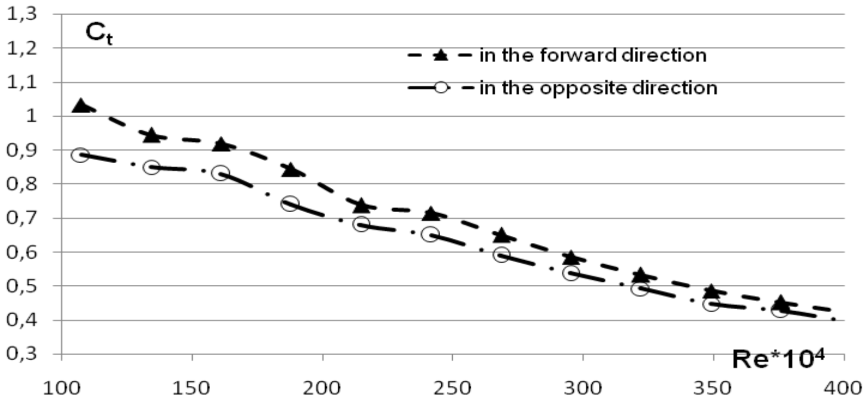


Fig. 8. The thrust coefficient dependence of WT-4 wind turbine on the Reynolds number

It is clearly seen that the type of dependence and the values of thrust coefficients practically match together. In the range of the Reynolds numbers between 60×10^4 - 400×10^4 the change in thrust coefficient ranges from 0.5 to 1. It was found that the wind turbine starts to operate efficiently at low wind speeds of 3 m/s and greater; it reaches the maximum power at wind speeds of 8-12 m/s.

Volt-ampere characteristic of WT-4 wind turbine at a fixed value of the pulley diameter were investigated. Figure 9 shows the dependence of the prototype model power of the wind-driven power plant. With increasing wind speed the generated power grows almost linearly, and at the speed of (6-7) m/s it is 3.5 kW. The maximum generated power is 5.5 kW at wind speed of 10 m/s.

Practice has shown that the main disadvantage of such wind turbines is their wind age that makes them attackable by strong gusts of wind and always requires special protective elements, which would remove wind overload in such cases. To avoid serious damage to the wind-driven power plant storm proofing was designed. The overload protection devices make not only for the reliability improvement of the design, but also for improvement of its performance under variable wind load that in some cases is equivalent to the increase in the wind energy efficiency [21].

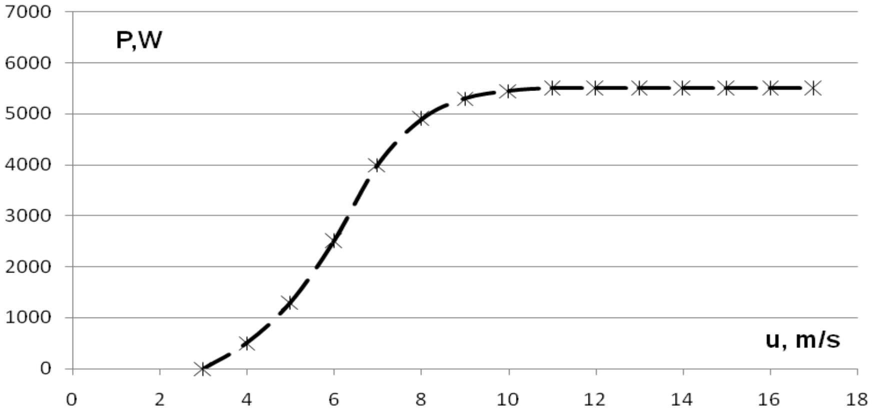


Fig.9. The power dependence of WT-4 wind turbine on the wind speed

5. A self-contained hybrid station based on WT- 4 wind turbine.

The presented wind-driven power plant is based on WT-4 sail-type wind turbine with the wind wheel diameter D=4 m. The nominal power of the designed self-contained hybrid station with an element of energy accumulation is 3.5 kW. In the hybrid system, the main source of energy is a wind turbine with blades with a dynamically variable surface shape. An additional energy source is a set of solar panels to generate electricity during periods of windless weather. Fig. 10 presents a scheme of a self-contained solar-wind station.

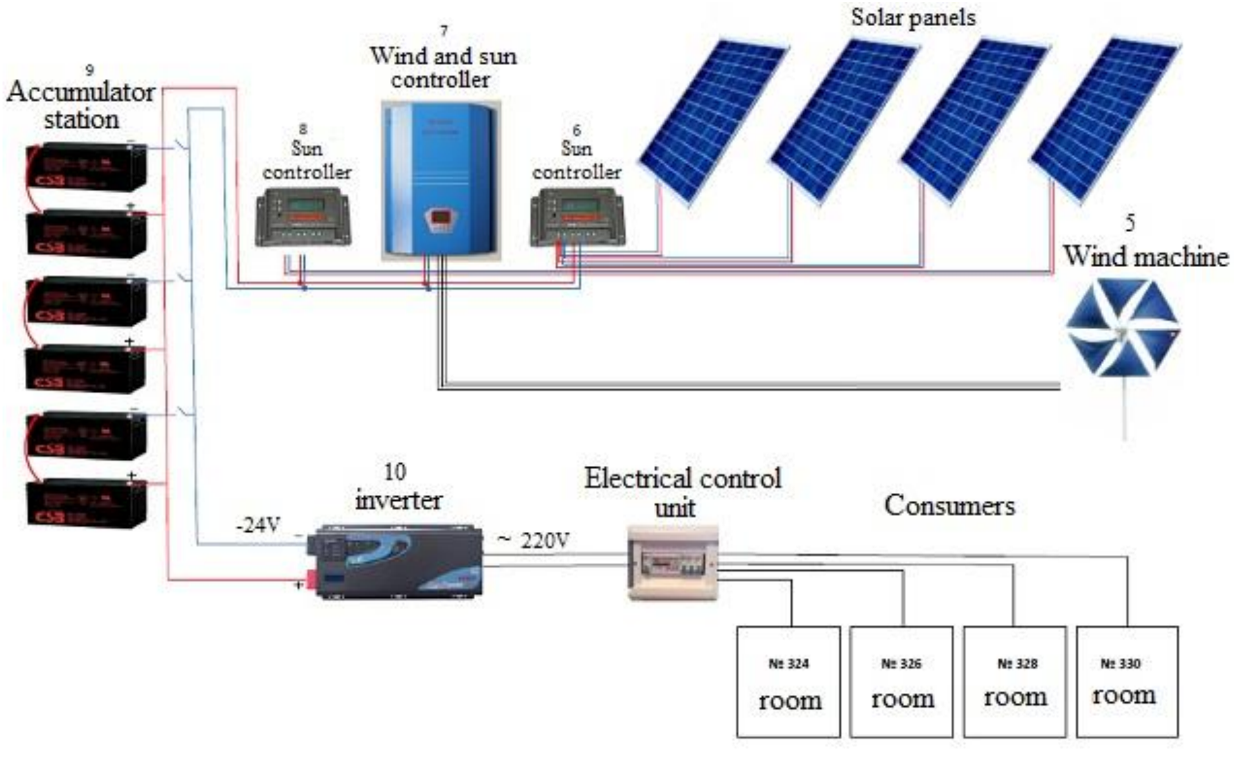


Fig.10. The scheme of a self-contained solar-wind station

The system consists of a wind turbine, a hybrid wind and sun controller (24 V, the power is 1000 W (wind) and 300 W (solar)), 2 additional solar controllers (24 V, 50 a), an inverter (2000 W, 220 V), an electrical control unit with installed 4 circuit breakers (220 V, 10 a) to supply 4 laboratories, 4 additional solar panels (with a capacity of 250 W, 24 V each), 6 electric accumulators (with a capacity of 150 a×h each, the total capacity of 450 a× h).

The wind-powered machine generates three-phase alternating current; the controller provides constant voltage to charge the electric accumulators, which is then converted by an inverter into alternating one. For the safety of the working staff in accordance with safety standards WT-4 wind turbine is blocked off, the enclosure area radius is 6 m. There is a portable weather station there. The wind-driven power plant is mounted at a height of 5 m above the surface of the Earth. For safety considerations in strong wind to reduce the working area of the wind wheel, the sail blades are tightened around the frame rods of the wind wheel. Additional equipment and control panel over the self-contained system of WT-4 wind turbine are located in a dry ventilated room with a constant temperature and humidity not exceeding 85%.

On average for a month the station produces 625 kW×h, which ensures normal operation of electrical appliances and computers, as well as illumination of laboratories with a total area of 158sq.m. The self-contained solar-wind station was tested throughout the year. The test results confirmed the possibility of the self-contained hybrid of station for regular electric power supply to 4 labs of Physics and Technology Faculty of E.A.Buketov KSU. Thus, the wind turbine design may be adopted as the base for operation at low wind speeds ranging between 3 m/s and 12 m/s.

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.

Thus, within the framework of the project the authors created an innovative product, i.e. wind-driven power plants, effectively operating at low flow rates of about 3 to 5 m/s using a wind turbine with a dynamically variable surface shape of the blades [patent]. Unlike propeller-type windmills, a sail-type wind turbine is silent. This fact is very important for the ecology of the area and the convenience of consumers. The wind turbine uses the ground wind energy. The advantage of the developed wind turbine is that the design does not require a turn of the wind turbine when a wind flow changes its direction. The advantages of the developed wind turbine may also include the following: low requirements to aerodynamic parameters of blades, which makes for producing them according to a short-cut technology of cheap materials in the form of sails with a rod frame; it is vibration-free and does not make high-frequency acoustic noise, ensuring sustainability when generating electrical energy, it is possible to maintain uniform speed of the wind turbine when the wind speed changes by changing the length of fastening cords of the blade movable ends.

In fact, low power sail-type wind engines rather efficiently convert energy of low speed wind (3-4m/sec). The presented wind machines with output power of 1.2kW, 3.5kW, 5.5 kW can be widely used for power supply to detached houses and small farms, far from centralized sources of electricity supply. Ease of construction, the possibility to assemble and disassemble rapidly, the mobility of the device is attractive for mountaineers, military servicemen (including frontiersmen, communication men, etc.) in field work.

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