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AP BI-DARRIEUS-1 WIND TURBINE

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Abstract: *There are a great variety of wind turbine constructions but by their principle of operation they are divided into three main types - sail (Savonius wind power unit), propeller and airfoils (Darrie wind turbine). At present, propeller-type wind-turbines are the most widely spread. They are produced on a commercial level in many countries. Other conditions being equal, the power produced by wind power unit (WPU) is proportional to the area being swept around by a wind wheel. Therefore, Megawatt propeller-type wind turbines have blades with the length of 40 and more meters. Only aircraft works with a highly-qualified personnel and corresponding equipment can produce such long blades of a specific shape. Of high interest have become airfoil wind turbines (Darrie WPU) lately. They are of a simpler construction and have a quite high wind power utilization factor (=0.45). In spite of the fact that this is a good index of WPU efficiency, the workers of al-Farabi Kazakh National University have developed a new version of a wind turbine which allows increasing 1.3-1.6 times the value of this coefficient. This apparatus is named a Bi-Darrie unit. This paper presents the description of a Bi-Darrie unit, the principle of its operation and the possibility of increasing the wind power utilization factor. Also, the results of testing an acting laboratory model in an aerodynamic tunnel and a full-length apparatus are reported. Video films are attached to the paper.*

Key words: *wind power engineering, vertical-axis wind turbine, Darrieus wind turbine*

1. Introduction

There are different types of wind turbines. The simplest of them is the wind turbine of sailing type (Savonius). Its feature is that it can be used with a vertical axis of rotation, as well as horizontal axis of rotation.

At present, wind turbines of propeller type are the most widely spread (see Fig.1). Historically developed traditions, as well as airplane propellers manufacturing techniques well mastered by industry are affected there. The so-called Camomile type also belongs to propeller type of wind turbine with a horizontal axis of rotation.

Recently a number of foreign firms and scientists began to prefer wind turbines of carousel-type with a vertical axis of rotation of the system Darrieus 1-3 (see Fig. 2 and 3). The symmetrical airfoil of NASA is used there for creation of torque (see Fig. 4).

Darrieus wind turbine has 2 diametrically opposite blades (see Fig. 2) (sometimes 3 equidistant from one another) which represent NASA airfoils symmetric toward the chord. These profiles are well approved and aerodynamic characteristics are known for each number 4-6.

The turbine operates due to generation of carrying capacity at operating blades equidistant from the general axis of rotation 7,8. Blades are placed uniformly around the radius r_0 in central vertical shaft of rotation and are connected to it by one of two ways: by matches or "troposkein".

The technique of fixing troposkein is that flat elastic operating wings are bent in the form of onions and both ends are attached to a rotation shaft. During the operation the turbine of the blade get a form of forcibly rotated sagged rope – troposkein (see Fig. 3). The Darrieus apparatus has the following advantages over propeller wind turbines: 1) in the result of vertical-axis rotation of the turbine the wind direction change has no importance; 2) the electrical generator and other equipment are placed at the earth level, that simplifies the machine design of great power, maintenance and repair; 3) structurally they are easy manufactured and has sufficiently high wind power efficiency (see Fig. 6).

Fig.1. Three-blade propeller wind turbine (England)

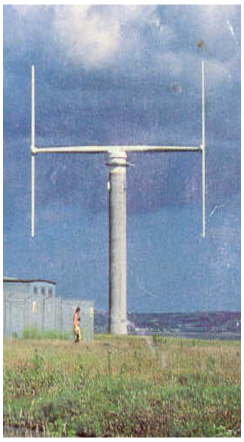

Fig.2. Wind-power unit with two-bladed turbine to Darrieus with direct blades (England)

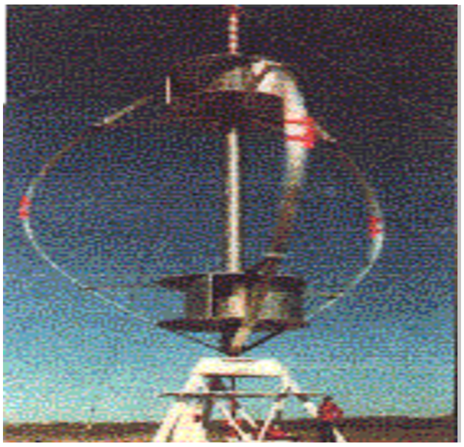

Fig.3. *Wind-power unit with three-blade turbine to Darrieus of system troposkein. Power - 30 kW. (Germany)*

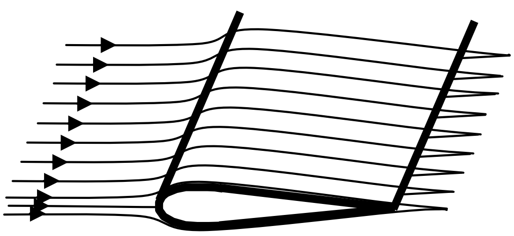

Fig. 4. *The scheme of NASA-0021 airfoil continuously flown around*

Maches are flat airfoil of span tied with a rotation shaft, to end faces of which operating blades are fixed so as blade chord would be directed along the tangent to the radius r_0 circle (see Fig. 2 and 3) 9.

According to technical-and-economic index these units do not yield to propeller-type turbines as well as exceed them when expanding capacity (see Fig. 7 and 8) 9,10. 4) symmetrical airfoil of NASA provide continuous flow of operating blades with wind stream and so the turbulence level of wind turbine decreases. 5) as it turned out the Darrieus wind turbine enables a wide range of constructive versions of these devices. 6) swept area doesn't concede to the propeller.

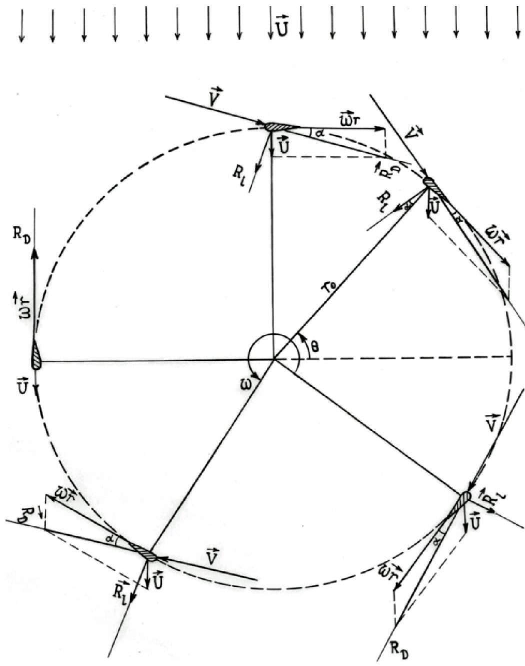

Fig. 5. *The scheme of one of operating blades of wind turbine rotating counterclockwise*

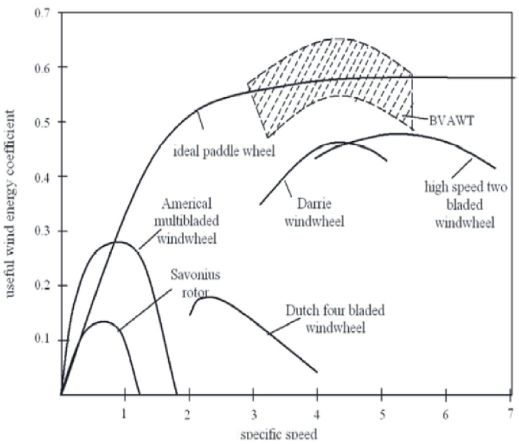

Fig. 6. *Dependencies of wind power utilization factor ξ for different types and constructions of wind turbine on the degree of their specific speed χ 9*

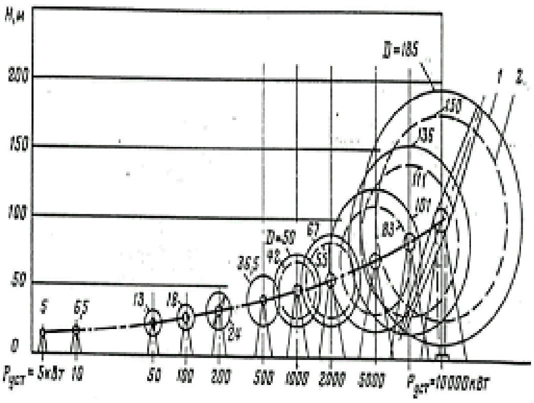

Fig.7. *Types of propeller wind turbines with a horizontal axis of rotation at an average annual wind speed of 7,6 m/s: 1 - in the territory far from the coast; 2 - on the coast (D – wind wheel diameter, m) 9*

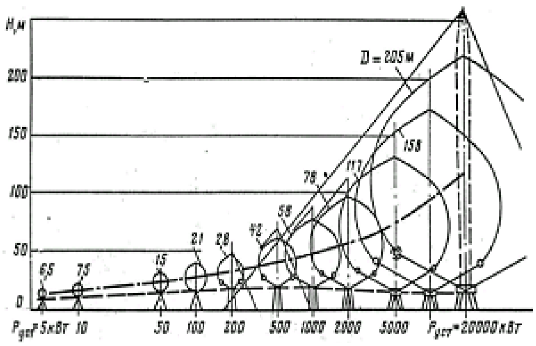

Fig.8. *Type of Darrieus wind turbines with a vertical axis of rotation at an average annual wind speed of 7,6 m/s 9*

2. BI-Darrieus turbine – 1

Darrieus wind turbine's maximum value of wind power use does not exceed the value ξ_{max}=0,45 (see. Fig.6) 9, 10. Despite the fact that it is good index of the turbine operation efficiency, employees of the Kazakh National University named Al-Farabi developed a new version of the turbine which allows increasing the effective value of this coefficient 1.3 times 11-17.

The proposed device consists of two coaxially located shafts. The turbine rotation takes place due to the action of carrying capacity on operating blades, which are positioned uniformly along the radius r_0 circle toward the vertical axis of rotation 12. Also, as in the known Darrieus wind turbine, the operating blades can be joined with the rotation shaft by Mach or by a "troposkein" method. A distinguishing peculiarity of a Bi-Darrieus-1 unit is a use of the principle of self-sufficiency operation of shafts in design which are jointed to the turbine and transfer wind power by current generators.

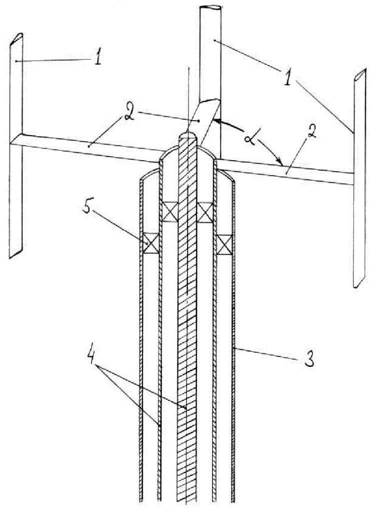

Fig. 9. *A principle scheme of a Bi-Darrieus1 with straight wings (one-side rotation): 1 - blades, 2 - shoulders, 3 - tower, 4 – rotation shafts, 5 – bearing, $\alpha = 90^0$.*

Fundamental constructive schemes of a Bi-Darrieus-1 wind turbine are shown in Figures 9-11. The first picture presents a variant with straight operating blades (1) of H–rotor. Each of the coaxially located shafts (4) is joined by maches (2) with its symmetrically located pair of blades (1) which, when rotating, create a moment of forces independently acting on its "own" shaft. In this variant, the both shafts must rotate to one side with an equal angular speed. A special correcting device was developed to support the angle $\alpha = 90^0$ at the work of a Bi-Darrieus-1. In the second picture, the scheme of work of a Bi-Darrieus-1 WDP is the same as in the first case, but the blades are in the form of troposkein. And finally, in the third picture - design which allows the shafts to rotate in opposite directions. Stability of the wind turbine operation is achieved by a symmetric position of the blades 11,12.

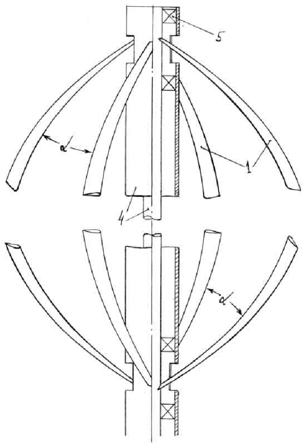

Fig. 10. *A principle scheme a Bi-Darrieus-1 of a troposkino system (one-side rotation). Denotations are the same as in Figure 9, ($\alpha = 90^0$).*

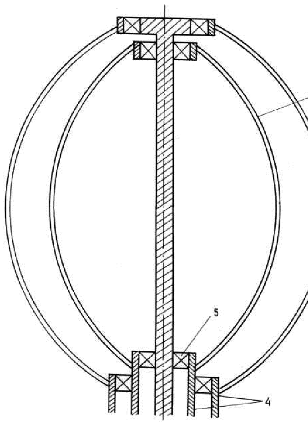

Fig. 11. A principle scheme a Bi-Darrieus-1 wind turbine construction with troposkein blades system (rotation of shafts in opposite directions). Denotations are the same as in Figure 9.

3. Results of theoretical research

The operation of a Bi-blade Darrieus-1 wind turbine is similar to common Darrieus but it has a higher value of an effective wind energy efficiency. This is explained by the inequality of the moment of forces acting on the blade which moves along the windward and leeward sides of the air flow.

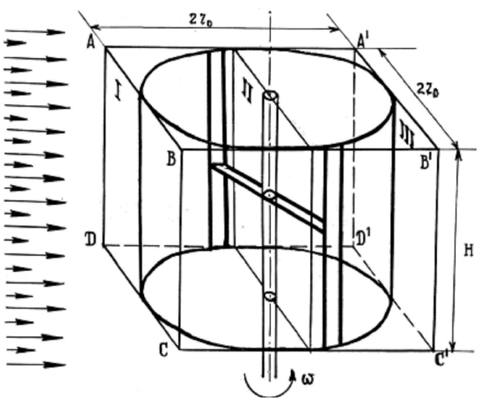

Fig 12.. A schematic picture demonstrating extraction of wind power by a Darrieus wind turbine from the windward and leeward sides.

As is known, power N_w which is transferred to the wind wheel of a Darrieus with straight operating blades is proportional to the swept area F, kinetic energy of wind $\rho U^3/2$ and energy efficiency (ξ). The value ξ depends on specific speed of rotor $\chi = W/U$, where W - linear rotation speed of rotor blades. Thus, unit power extracted from unit of the swept area is expressed by the formula:

$$\overline{N}_{в} = \xi F \rho \frac{U^3}{2} \qquad (1)$$

Figure 12 schematically shows area F which is the side surface of the cylinder with radius r_0 and height H.

In order to show the essence of the proposed solution, let us consider a rectangular parallelepiped of ABCDA'B'C'D' containing surface F. The upper and lower faces of a parallelepiped go through the end planes of the cylinder and the other four ones are mutually touch its side surface. The parallelepiped is oriented so that two side faces (on the left and right of the cylinder) are perpendicular to a wind flow and the second pair is parallel to it. Let us construct another plane which is perpendicular to the direction of a wind and goes through the axis of the cylinder. Thus, we have three control surfaces (I), (II), (III), the area of each of them is equal to midship section ($S = 2r_0H$) of the side surface of cylinder F. As is seen in Figure. 9, Darrieus unit uses maximum 45% (ξ_{max}= 0,45) of the wind power and transfers it to the shaft. Then the question is what portion of this power is extracted from the windward side of surface F being swept around (the left side of cylinder Figure. 13) and leeward side (the right side of F). Let us see energy flows through control surfaces (I), (II), (III):

а) the density of wind power flow through control surface (I) is equal to

$$\overline{N}_{вI} = \rho \frac{U^3}{2} \qquad (2)$$

б) after passing the left half of swept cylindric surface and transferring part of its power to blades of wind turbine, density of wind power decreases by value "k", and will go through control surface (II) with specific power

$$\overline{N}_{вII} = (1-k)\rho \frac{U^3}{2} \qquad (3)$$

в) when crossing the right side surface of cylinder F, the wind will also lose "k"-part of its power $\overline{N}_{wII}$ and will go through control surface (III) which is behind the wind turbine with specific density of power flow

$$\overline{N}_{вIII} = (1-k)\rho \frac{U^3}{2} - k(1-k)\rho \frac{U^3}{2} \qquad (4)$$

On the other hand, it is known, that the total amount of specific power extracted by a Darrieus wind turbine is determined by formula (1). Hence, behind the wind turbine or, which is the same behind the control surface (III) the density of wind power flow decreases by $(1-\xi)$ times:

$$\overline{N}_{вIII} = (1-\xi)\frac{\rho U^3}{2} \qquad (5)$$

Equating expressions (4) and (5), we find out that $k = 1 - \sqrt{1 - \xi}$.

If we take $\xi_{\max} = 0{,}45$ we will get that 26% of power of the total amount of wind power is extracted from the windward side and the rest 19% - from the leeward side. This fact makes it possible to extract an appreciably greater amount of wind power from one and the same swept surface *F*, if two equally sized Darrieus wind turbines rotating in one direction (there may be constructions with rotation of turbines in opposite directions (see Fig. 11)

The greatest effect is achieved, when using the two-blade wind turbines set up at an angle 90^o with respect to each other. Then, every time, passing around the windward side, the turbine blades will extract 26% of energy each from the continuously flowing undisturbed current and transfer it to their current generators via their own shafts. Naturally, from the leeward side energy is extracted from the twice weakened wind. Unlike in case of a simple Darrieus, the specific power will decrease 2 k times.

Thus, two Bi-Darrieus-1 wind wheels will extract 26% of energy each from the side of fresh air and only 12% each from the leeward side as $k_m(1 - 2k_m) = 0{,}1248$, index “m” indicates that k_m corresponds $\xi_{\max}$. In the total, each generator transforms 38% of power into electricity that will make up the sum 76% against 45% in case of a Darrieus turbine.

4. Results of a pilot study

Experiments were made on the acting laboratory model of the wind turbine with direct operating blades in a wind tunnel of JSC Scientific Research Institute.

“Gidropribor”. Characteristics of a stream were measured in a working site of a wind tunnel.

Design of universal model of carousel type wind turbine

The model is a two-bladed variant with a twin vertical straight operating blades fixed to the horizontal direction of maches deployed on 180^0. Operating blades and maches are symmetric profiles of NASA-0021 (see. Fig. 13). Two such two-bladed wind turbines mounted on two coaxial shafts which may rotate independently of each other. Dimensions of wind turbines are identical and four operating blades arranged at the same distance from the common axis of rotation, in other words, the lengths of maches are identical. Maches are attached to the top of the shaft. Each of the coaxial shafts has pulley, by belt transmission rotates two independently operating electrical generators. Wind turbines are deployed relatively to each other at 90^0, so that the turbine’s maches crossbar with right angles. There is a special device for independent rotation of turbines that supports this angle constant. Thus, each turbine rotates its own shaft and transmits the torque to one of the generators. Such a device represents the model of "Bi-Darrieus", the ability to rotate 2 power generators simultaneously.

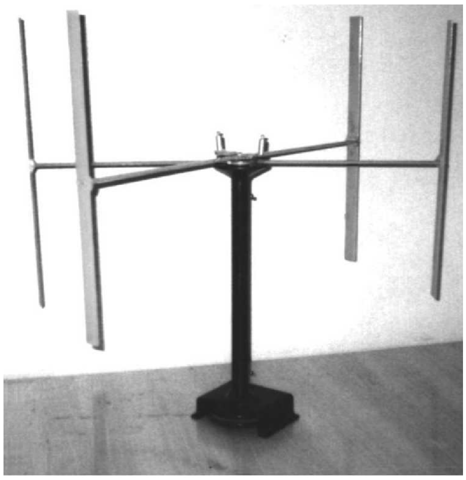

Fig.13. *The acting laboratory model of the Bi-Darrieus turbine*

The design allows removing one of the turbines connected to the inner shaft. In this case we have a well-known model of two-bladed turbine, "Darrieus", which transmits energy to a single generator through the rotation shaft. As a result, we can compare the power developed by wind turbines "Bi-Darrieus" (total power of two power generators) and "Darrieus" with all other equal conditions.

Dimensions of the wind turbine are selected so that the entire model was placed in the working section of the wind tunnel. It is an open section of elliptical shape with dimensions: length - 2,2 m, the major axis of the ellipse - 2,1 m located in the horizontal direction, the minor axis - 1,2 m. The air flow moves in the work area in horizontal direction at speed up to 35 m/s (see. Figure 14).

The model was mounted in the central part of the work area of wind tunnel perpendicular to the flow so that the plane of rotation of maches lye in the central plane of the working area, passing through the major axis of the ellipse and the axis of rotation of the turbine is directed along the minor axis of the ellipse (see. Figure 15).

Dimensions of the model: the height from the pulley to the plane of rotation of maches - 0,51 m length of maches from the axis of the turbine to the operating wing chord, equal to the radius of rotation - 0,404 m, the length of the working vane

(T - mount) - 0,55 m, chord working blades and swings - 0.03 m (NASA-profile 0021).

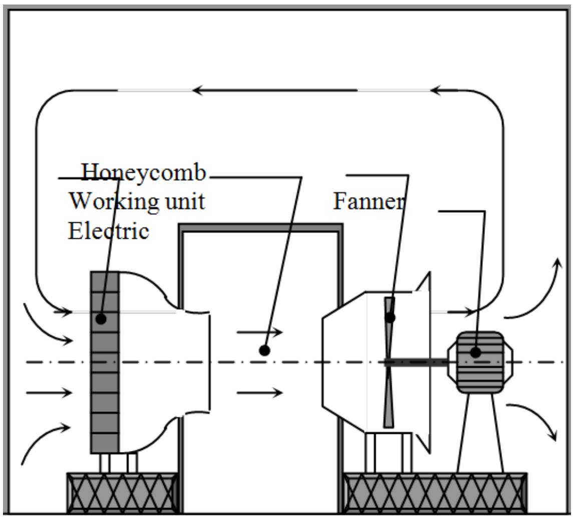

Figure 14. A principle scheme of a wind tunnel

Figure 15. *The active laboratory model of the Bi-Darrieus turbine in a working site of a wind tunnel (top view)*

Test program.

Research required the development of a test program.

Universal laboratory model of a wind turbine of carousel type allowed exploring the work of the device in both "Darrieus" and "Bi-Darrieus". In this connection, the test program is aimed to perform:

1. To test the model in regime "Darrieus" on no-load operation in order to clarify the nature of its rotation in the air stream.
2. To test the model of "Darrieus" with several current generators for use in experiment that is the most suitable among them.
3. To perform several series of experiments with the model in the regime of "Darrieus" and "Bi-Darrieus" to obtain comparative characteristics, which is the main objective of the test carried out.
4. To Carry out an aerodynamic measurement in the flow at the rotary wind turbine model in order to clarify the effect of the rotating turbine on a wind flow.

Test results.

The possibility of quantitative power recording developed by the turbine, allowed performing four series of experiments. We were interested in the repeatability of the results, as well as the expansion of the experimental data while varying the various elements of the electrical part, because, as noted above, the stationary remote control and measurements were not performed.

In each series of experiments, measurements were made with a permutation of generators, connecting them with the belt drive or other shafts. Similarly rheostats were varied when removing power, as well as the measurement of current and EMF carried out with one devices or the others. The data obtained are summarized in Table 1.

In the last column of the table (the far right column) power is indicated, produced in the "Darrieus" regime, and the total capacity of two power generators during operation of the turbine in "Bi-Darrieus" regime. As the table shows, in all experiments the total power of "Bi-Darrieus" is higher for 30-40% than in "Darrieus".

Upon completion of the tests an aerodynamic experiment was conducted by three-chanel decoder for analyzing the distribution of the field speed and pressure before the turbine inside cylindrical surface swept by rotor blades, and behind, of wind turbine.

4. Conclusions

The article describes the design and operation of a new modified model proposed by the authors Bi-Darrieus has a high wind energy use efficiency, the prototype of which is the Darrieus wind turbine. A theoretical and experimental works were carried out, and reliable results were obtained, which confirms the increase in the maximum wind power use efficiency at Bi-Darrieus by 1.4 times comparing with the maximum wind energy use efficiency of existing modern wind turbines in the world.

The design of the wind turbine Bi-Darrieus has no analogue in the world, so the more complete description of the technical and theoretical basis was given, i.e. mathematical statement, describing the calculation of wind energy use efficiency of turbines. As well as description of the technical characteristics of manufacture of universal laboratory model (works in both Darrieus and Bi-Darrieus regimes) and its testing in the wind tunnel are given. Under preparation and conducting a series of experimental research of laboratory model great jobs were performed, to state them in one article is impossible. The results of serial experimental studies are given in tabular form. Received theoretical as well as experimental data suggest that wind turbine energy use efficiency of the proposed Bi-Darrieus turbine is 1.4 times higher comparing with the Darrieus wind turbine.

In addition, a semi-industrial embodiment of Bi-Darrieus wind turbine with counter-rotating working blades was manufactured. Also the full scale testing is performed on it.

Table 1. Results of tests «Darrieus» and «Bi-Darrieus» wind turbines

№ of experience	regime	No-load operation		Work with loading				
		Cycles per minute	Generator voltage (W)	Cycles per minute	Generator voltage (W)	Current (mA)	Wattage (Wt)	Total power (Wt)
	I-a series of experiments							
1.	2 bladed «Darrieus» (1 eng.)	800		450	3	130	0,39	0,39
2.	«Bi-Darrieus» (1 eng.)	700		400	2,5	110	0,275	0,55
	(2 eng.)	700		400	2,5	110	0,275	
	II -a series of experiments							
1.	2 bladed «Darrieus» rheostats 2,1 (1 eng.)	500	5	450	3	100	0,3	0,3
2.	«Bi-Darrieus» rheostats 2,1 (1 eng.)	400	3,8	350	2,2	95	0,21	0,386
	(2 eng.)	400	3,8	350	2,2	80	0,176	
3.	«Bi-Darrieus» rheostats 1,2 (1 двиг. eng)	400	3,8	350	2,4	80	0,19	0,41
	(2 eng.)	400	3,8	350	2,2	100	0,22	
	III- a series of experiments, engines traded places							
1.	«Bi-Darrieus» rheostats 1,2 (2 eng.)	420	4	390	2,5	90	0,225	0,435
	(1 eng.)	420	4	390	2,2	95	0,21	
2.	«Bi-Darrieus» rheostats 2,1 (1 eng.)	450	4	390	2,4	85	0,204	0,468
	(2 eng.)	450	4	390	2,4	110	0,264	
3.	«Bi-Darrieus» with densely twirled by springs rheostats 2,1 (2 eng.)	400	3,4	300	2,0	70	0,14	0,338
	(1 eng.)	400	3,4	300	2,2	90	0,198	
4.	2 bladed «Darrieus» rheostats 2,1 (2 eng.)	500	4,5	400	2,9	125	0,36	0,36
5.	2 bladed «Darrieus» rheostats 1,2 (2 eng.)	500	4,5	420	3	105	0,315	0,315
	IV - a series of experiments, engines traded places							
1.	«Bi-Darrieus» rheostats 2,1 (2 eng.)	450	3,8	350	2,2	100	0,22	0,472
	(1 eng.)	450	4	350	2,4	105	0,252	
2.	«Bi-Darrieus» rheostats 1,2 (1 eng.)	450	3,8	380	2,2	120	0,264	0,498
	(2 eng.)	450	4	380	2,6	90	0,234	
3.	«Bi-Darrieus» with densely twirled by springs rheostats 1,2 (2 eng.)	400	3,2	350	2,0	120	0,24	0,465
	(1 eng.)	400	3,4	350	2,5	90	0,225	
4.	«Bi-Darrieus» with densely twirled by springs rheostats 2,1 (2 eng.)	400	3,2	320	2,2	90	0,198	0,438
	(1 eng.)	400	3,4	320	2,4	120	0,24	
5.	2 bladed «Darrieus» inner shaft rheostats 1,2 (1 eng.)	500	4,5	400	2,6	120	0,312	0,312
6.	2 bladed «Darrieus» inner shaft rheostats 2,1 (1 eng.)	500	4,5	420	2,8	100	0,28	0,28

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