The energy efficiency research of combined H-Darier-Savonius rotors for autonomous power supply of objects on land and at sea

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Abstract. For the first time, the experimental energy efficiency research of combined rotors of vertical-axial wind mill based on improved H-Darier and Savonius rotors, which have blades with flaps, were performed. The experiments have shown that the maximum power factor value of combined rotors reached 0.60, which is almost 1.5–2.0 times higher than that of commercially produced horizontal-axial wind mills. The semi-empirical formula is obtained that allows determining the power factor of the combined rotor with different geometric dimensions of the H-Darier and Savonius rotors that are part of it with different numbers of stages. Energetically, economically and ecologically efficient wind mills with combined rotors with the capacity of 1–10 kW can be used for autonomous power supply of heat supply, water supply of various facilities, for oil production on land and at sea, as well as for driving propellers of small vessels.

1. Introduction

In many countries, the decentralized energy supply systems using wind mills are becoming more widely used [1–4]. Along with the horizontal-axial wind mills (HA WM), since 1980s, the vertical-axis wind mills (VA WM) have also been used. The operation of these installations does not depend on the wind direction. The VA WM based on the H-Darier rotor with the vertical wing profile blades and the Savonius rotor with vertical semi-cylindrical blades are most often used [5–13]. The main advantage of H-Darier rotors is their speed, and the main disadvantage is the inability to self-start due to a small starting torque, especially at low wind speeds. The main advantage of Savonius rotors is their ability to self-start due to the large starting torque, and the main disadvantage is the low speed of rotation. These advantages of VA WM rotors in comparison with the most widespread HA WM rotors make them ideal sources of low power for consumers of electric and thermal energy, objects that are remote from the centralized power supply, heat supply and water supply systems. These H-Darier and Savonius rotors and their various combinations can be used not only on land, but also at sea for power supply of vessels and for driving propellers of small vessels [14, 15].

Previous research [17–22] showed that optimization of the H-Darier and Savonius rotor designs and the use of blades with zigzag flaps allowed to increase significantly their energy efficiency. It was experimentally proved that the maximum energy efficiency (power factor) of the improved H-Darier rotor reached the value of 0.72 exceeding the maximum possible value of 0.45 for the HA WM, and the maximum power factor of the improved Savonius rotor reached the value of 0.32 , significantly
exceeding the value of 0.20 for the known types of Savonius rotor. It should be noted that the maximum possible value for the HA WM is the value $C_p = 0.45$ which is achieved only when the wind speed coincides with the axis of rotation of the rotor. If they have enough inertial wind orientation control systems, the actual power factor is reduced to 0.25–0.35. Therefore, the upgraded design of the Savonius rotor proposed by the authors with the maximum possible power factor value of 0.32 can be quite competitive with the HA WM. As it has been already noted, the main disadvantage of the H-Darier rotor is its inability to self-start due to the small starting torque. Therefore, it is quite relevant to create a combined H-Darier-Savonius rotor (CDSR) based on the improved H-Darier and Savonius rotors by the authors, which have optimal size ratios and blades with zigzag flaps.

The aim of this work is to develop the improved VA WM based on the CDSR. The main objectives of the work are: experimental research and analysis of the energy efficiency of CRDS having optimal size ratios and blades with zigzag flaps, obtaining the generalizing dependence for determining the power factor of CDSR, as well as evaluating the possibilities of their application in the VA WM for autonomous power supply of various objects on land and at sea.

2. Methods of conducting experiments

In 2019, the alternative energy laboratory of the department of energy problems of the Saratov scientific center of the Russian Academy of Sciences at the Astrakhan state technical university developed a modernized laboratory installation for experimental research of the CDSR efficiency having flaps. The general view of this experimental laboratory installation is shown in figure 1.

![Figure 1. The general view of the experimental laboratory installation for the research of combined H-Darier-Savonius rotors with flaps.](image-url)

The source of air flow was a more powerful fan than previously [13–15], which allows achieving air flow speeds of up to 9–10 m/s. A coordinate device in the form of a frame with a grid of thick synthetic yarns on $3 \times 6$ cells with size $0.10 \times 0.10$ m was used to determine the speed of air flow at fifteen points (centers of cells). The average speed of the air flow $V$ in each of the sections at a distance $x$ from the fan was determined using a digital anemometer with an error of no more than 0.1 m/s based on averaging the flow rates at fifteen points. By changing the distance to the rotor axis, the average cross-section speed of the air flow was changed. The torque of the rotor was balanced by the moment of elastic force of the stretched spring (dynamometer). The left stationary part was attached to synthetic yarn that ran along the brake pulley and was attached to the fixed rod. The spring strain was measured on the appropriate scale. The combined H-Darier-Savonius rotor was mounted on a single shaft with the brake pulley and the multiplier pulley. The rotor speed was measured using a DC power generator with a V-belt multiplier with a gear ratio of 7.09 to increase the frequency of...
rotation of the generator shaft. The axial industrial fan with the impeller diameter of 0.45 m is enclosed in the square casing with the safety net.

The H-Darier rotor with the diameter of \( D_D = 0.320 \) m has 3 blades with the profile width of \( b_D = 0.100 \) m, the height of \( H_D = 0.300 \) m and the profile thickness of \( \delta_D = 0.012 \) m. The blades also include zig-zag flaps with triangular elements 0.010 m high. Two two-stage Savonius rotors of optimal geometry with various sizes were used: diameter \( D_S = 0.185 \) m and \( D_S = 0.0925 \) m, four blades with the opening angle \( \theta = 135^\circ \), diameter \( D_{PS} = 0.100 \) m and \( D_{PS} = 0.050 \) m, height \( H_{PS} = 0.140 \) m and \( H_{PS} = 0.070 \) m. The blades include front and rear generators with triangular elements (flaps) 0.010 m high. The first Savonius rotor is shown in figure 1a, and the second – in figure 1b.

The experiments were performed when the average air flow speed changed from 2.7 m/s to 7.2 m/s. Such a range of air flow speeds practically corresponds to the real range of changes in wind speed on land and at sea, at which VA WM on the basis of CDSR can be operated. Processing of the results of parameters measurements of combined rotors was performed, as before, according to the method given in works [18–22]. In particular, the digital voltmeter that measures the electromotive force of the electric generator \( E \) was used to determine the speed of the CDSR, rpm:

\[
\text{n} = K_n \cdot E, \text{rpm,} \tag{1}
\]

where \( K_n \) – calibration constant, rpm: B.

The effective power of the CDSR, Watt, was determined by the formula:

\[
P_{DS} = \frac{1}{60} K_G \Delta x D \pi n, \text{n}\cdot m. \tag{2}
\]

Where \( K_G \) – calibration constant of the dynamometer, n/m; \( \Delta x \) – spring deflection, m; \( D \) – the pulley diameter for measuring the elastic forces, m.

The results of determining the main parameters of the CDSR are shown in figure 2.

![Figure 2](image)

**Figure 2.** The main parameters of the CDSR:
- a – the dependence of the average air flow speed on the distance from the CRDS axis to the fan body;
- b – the dependence of the CRDS power on the air flow speed.

3. **Discussion of the obtained results**

As seen in figure 1a as the distance increases from 0.45 to 3.0 m the average air speed is reduced from 7.2 to 2.7 m/s, that is 2.7 times that leads to a change in airflow capacity proportional to speed cubed in 19 times. This range of air flow speeds practically corresponds to the real range of changes in wind speed on land and at sea, at which CDSR can be operated.

The dependence of the experimental CDSR power on the air flow speed is shown in figure 2b. With an increase in the air flow speed from 2.7 to 7.2 m/s, that is, by 2.7 times, the rotor power increased from 0.60 to 9.91 W, that is, by 17 times. A slightly lower degree of increase in the useful
power of CDSR with the increase in the air flow speed, in comparison with the degree of increase in the spent air flow power from the speed, is explained by the decrease in the power factor (energy efficiency) at high speeds. At low air flow speeds, the Savonius rotor promotes straining and spinning of the combined rotor, and at high wind speeds, the H-Darier rotor begins to slow down [7, 8]. The question about optimizing the ratio of geometric parameters of the H-Darier and Savonius rotor as part of the combined rotor requires further research.

We also experimentally determined the power coefficients of CDSR having blades with flaps and the speed coefficients $Z$ according to the method given in the works of the authors [21–25]. Figure 3 shows the dependence of the power coefficients of the CDSR, which have blades with flaps, on the speed coefficient $Z$.

![Figure 3](image.png)

**Figure 3.** The dependences of the power coefficients of the H-Darier rotor (1), CDSR (2, 3), and the Savonius rotor (4), which have blades with flaps, on the speed coefficient $Z$.

As it can be seen from figure 3, all the rotor power coefficients curves have a pronounced maximum at different values of $Z$ from the speed coefficients $Z$, depending on the rotor design. The obtained maximum values of the $C_p$ CDSR coefficient (curve 2) are $C_p = 0.60$ for smaller Savonius rotor sizes $D_S = 0.0925$ m, $D_S = 0.050$ m, $H_S = 0.070$ m and $C_p = 0.40$ (curve 3) for larger Savonius rotor sizes $D_S = 0.185$ m, $D_S = 0.185$ m, $H_S = 0.140$ m. At low air flow speeds, the Savonius rotor promotes breakaway and spin up of the combined rotor, and at high wind speeds the H-Darier rotor begins to slow down. This leads to significantly higher values of the CDSR power factor with a smaller size of the Savonius rotor that is part of it. For comparison, the dependence of the power coefficients of the H-Darier rotor (curve 1) and the Savonius rotor (curve 4), which have blades with flaps, on the speed coefficient $Z$ is also shown. The maximum value of the power coefficients is $C_p = 0.72$ for the H-Darier rotor and $C_p = 0.32$ for the Savonius rotor. The maxima of all curves 1-4 marked with points depend on the speed coefficients $Z$, varying from 0.71 for the Savonius rotor to 1.23 for the H-Darier rotor.

Thus, the CDSR developed by the authors has the speed characteristic of the H-Darier rotor and the ability to self-start due to the large starting torque of the Savonius rotor, even at low wind speeds of 2-3 m/s. In contrast to the HA WM, the operation VA WM based on CDSR does not depend on the wind direction, and therefore the specific energy output of similar power structures in these wind mills will be 1.5–2.5 times higher.
4. Obtaining the generalizing dependence for determining the power factor of the CDSR

The useful power of the CDSR when the Savonius rotor is moved outside of the H-Darier rotor can be determined by the formula proposed by the authors:

\[ P_{RDS} = \frac{1}{2} \rho V^3 \eta_1 \left( C_{PD} S_D + C_{ps} S_S \right) = \frac{1}{2} \rho V^3 \eta_1 \left( C_{PD} N_D D_D H_D + C_{ps} N_S D_S H_S \right), \tag{3} \]

where \( \rho \) – air density, kg/m\(^3\); \( V \) – air speed, m/s; \( \eta_1 \) – coefficient that takes into account the reduced efficiency of the combined rotor compared to the H-Darier rotor; \( C_{PD} \), \( C_{ps} \) – the power coefficients of the H-Darier and Savonius rotors; \( S_D \), \( S_S \) – swept areas by the rotor; \( m^2; N_D \), \( N_S \) – the stage numbers of the H-Darier and Savonius rotors.

The power of the wind flow within the swept areas by the rotors can be determined by the formula

\[ P = \frac{1}{2} \rho V^3 \left( C_{PD} S_D + C_{ps} S_S \right) = \frac{1}{2} \rho V^3 \left( C_{PD} N_D D_D H_D + C_{ps} N_S D_S H_S \right). \tag{4} \]

The power factor of the CDSR can be defined as the ratio of the CDSR useful power to the wind power by the formula

\[ C_{pDS} = \eta_1 \frac{C_{PD} + C_{ps} \frac{S_S}{S_D}}{1 + \frac{S_S}{S_D}} = \eta_1 \frac{C_{PD} + C_{ps} \frac{N_S D_S H_S}{N_D D_D H_D}}{1 + \frac{N_S D_S H_S}{N_D D_D H_D}}. \tag{5} \]

The empirical coefficient \( \eta_1 \) takes into account the reduced efficiency of the combined rotor compared to the H-Darier rotor due to the fact that the maximum efficiency of the Savonius and H-Darier rotors is achieved at different values of the speed coefficient \( Z \). It can be expressed from the formula (5)

\[ \eta_1 = \frac{C_{pDS} \left( 1 + \frac{S_S}{S_D} \right)}{C_{PD} + C_{ps} \frac{S_S}{S_D}} = \eta_1 \frac{C_{pDS} \left( 1 + \frac{N_S D_S H_S}{N_D D_D H_D} \right)}{C_{PD} + C_{ps} \frac{N_S D_S H_S}{N_D D_D H_D}}. \tag{6} \]

Substituting in the formula (6) the experimental data on the basis of 18 values of the CDSR power coefficients, the rotor H-Darier, the Savonius rotor, and the ratio of the swept area by the Savonius rotors and H-Darier rotors were calculated the values for the empirical factor \( \eta_1 \).

The average value of this coefficient was \( \eta_1 = 0.78 \). Substituting this value in the generalizing formula (5), it is possible to determine the power factor value of the CDSR at different geometric sizes of the rotors included in it: the H-Darier \( (D_D, H_D) \) and the Savonius \( (D_S, H_S) \) with a different stage numbers of the rotors \( N_D, N_S \).

The question about optimizing the ratio of the geometric parameters of the H-Darier and the Savonius rotor, in particular, the size and the shape of the zigzag flaps, in the CDSR requires further research. In 2020, it is planned to develop and test a larger experimental VA WM with CDSR with flaps in full-scale conditions and compare its main parameters with mass-produced VA WM.

5. The possibility assessment of using the VA WM based on the CDSR for autonomous power supply, heat supply and water supply

The technical and economic efficiency assessment of the original VA WM based on CDSR with zigzag flap blades shows that they will have a specific capital cost of no more than 106 thousand rubles/kW = 1.68 thousand dollars/kW = 1.53 thousand euros/kW (at the exchange rate of 30.01.2020). The payback period with appropriate state support will be no more than 6.6 years. Therefore, these VA WM will be competitive with other types of commercially available wind mills. These VA WM with the capacity of 1-10 kW can be used at various facilities that are remote from the centralized power, heat and water supply systems. These VA WM can be used together with other renewable energy sources and fuel and energy resources.

As it is noted in the work [13], VA WM of GRC-Vertical LLC, in contrast to the HA WM, is not generators of infrasound and noise. The same can be said about the VA WM based on the CDSR.
Therefore, these VA WM can also be used at sites that have high environmental requirements, i.e. in nature reserves and national parks. They can be used for generating electric and thermal energy (together with thermal heaters), either independently or in combination with solar batteries [18].

The energy-efficient and cost-effective VA WM with CDSR with zig-zag flap blades having the capacity of 5–10 kW can be primarily used for autonomous power supply of various small objects on land and at sea. For power supply of low-rise buildings, farms, tourist complexes, fishing and other facilities, for electric driven installations for oil production, both on land and at sea [14, 19]. CDSR with flaps can also be used for power supply of river and sea vessels, as well as for driving propellers of small vessels [17].

The thermal heaters, mechanical heat generators, and heat pump installations can be used to generate heat energy by VA WM with CDSR. The use of heat and electric heaters in some cases will be preferable, for example, for heating small objects. However, the wind energy is first converted into mechanical, then electrical, and finally thermal. In this case, at $C_F = 0.60$ the CDSR, the overall efficiency of the wind-heat installation will be 0.48–0.54. In addition, the proposed CDSR can be aggregated with original mechanical heat generators in which the mechanical energy of the rotating CRDS is converted into thermal energy due to the friction forces of high-viscosity liquid between the rotating disks connected kinematic to the CDSR shaft and fixed disks [23]. In this case, the overall efficiency of the wind-heat installation can be 0.54–0.57, and the heating time of the coolant to 50–60°C will be about 5 hours. This technical solution will be more effective from the energy and technical and economic points of view. VA WM with CDSR can be used to generate electricity used to drive heat pump compressors. This will allow providing heat supply to small objects in the presence of ground, water, and air heat sources. With the heat conversion coefficient of 3–4 by heat pumps, the overall efficiency coefficient of the wind-heat installation can reach 1.8–2.4. All 3 options can be used for autonomous heat supply of various objects. The capacity of the VA WM with CDSR is quite sufficient for autonomous heat supply of low-rise buildings, farms, tourist complexes, buildings in nature reserves, national parks, and other autonomous objects [18, 23]. The choice of heat supply options for specific facilities will be determined by technical and economic calculations.

In addition, the VA WM with a power of 1–10 kW can be used for water lifting. In this case, they will be able to increase the water supply by 2–3 times due to a higher power factor of the CDSR compared to widely used horizontal-axial multi-blade wind-lifting installations. Therefore, their use in autonomous water supply systems, as well as in water use systems for watering various plants will be more energy-efficient and cost-effective.

6. Conclusion

1. The improved VA WM based on the CDSR with zigzag flaps were proposed. Their start was carried out using the Savonius rotors, and the operation of the rotor was carried out using the rotor H-Darier with diameter and height of 3–4 times more than the Savonius rotor.

2. The experiments have shown that with the increase in the average air speed from 2.7 to 7.2 m/s, the air flow power and the power of the CDSR increased in 19 times. At the same time, the maximum values of the CDSR power factor reached 0.60, which is almost in 2 times higher than that of commercially produced horizontal-axial WM with a power factor of 0.30–0.40.

3. The semi-empirical universal formula is obtained that allows determining the power factor of the CDSR at different geometric sizes that are part of the H-Darier and the Savonius rotors with different stage numbers of rotors.

4. The energetically, economically and environmentally efficient VA WM with CDSR will be quite competitive with other types of wind mills. Therefore, these VA WM with the capacity of 1–10 kW can be used for autonomous power supply, heat supply and water supply. To obtain heat energy, it is advisable to use mechanical heat generators and heat pump installations in conjunction with the VA WM with CDSR. They can be used for power supply of low-rise buildings, farms, tourist complexes, fishing facilities and other facilities, for electric driven installations for oil production, both on land and at sea.
The CDSR with flaps can also be used for power supply of river and sea vessels, as well as for driving propellers of small vessels.

References

[1] Kiushkina V R and Sharipova A R. 2014 Trends in energy decentralization and ways to improve small power Industrial energy 5 2–8
[2] Gabderakhmanova T S and Director L B 2015 The analysis of autonomous power supply schemes based on renewable energy sources Industrial energy 4 48–51
[3] Chemekov V V and Kharchenko V V 2013 The heat supply system for a self-contained dwelling house on the basis of a heat pump and wind power installation Thermal Engineering 60 212–6
[4] Chivenkov A I, Loskutov A B and Mikhailichenko E A 2012 The application and development analysis of wind turbines Industrial energy 5 57–63
[5] Lyakhter V M and Shpolyansky Yu B 1988 Aerodynamics of orthogonal wind turbines Collection of Research papers Gidroproekt, Issue 129: Wind power stations 113–27
[6] Solomin E V 2011 Methodology of development and creation of vertical-axial wind power plants: monograph (Chelyabinsk: SUSU Publishing house) p 324
[7] Baklushin P G, Vashkevich K P, Samsonov V V 1988 The experimental research of aerodynamic characteristics of orthogonal winged wind wheels Collection of Research papers Gidroproekt 98–105
[8] Gorelov D N 2010 Energy characteristics of the Darier rotor (review) Thermophysics and Aeromechanics 17 325–33
[9] Gorelov D N 2003 The problems of Darier wind wheel aerodynamics Thermophysics and Aeromechanics 10 47–51
[10] Gorelov D N 2012 Aerodynamics of wind wheels with the vertical axis of rotation Omsk branch of the Sobolev Institute of mathematics SB RAS (Omsk: polygraph center KAN) p 68
[11] Forando, Modi 1988 Characteristics of the Savonius wind turbine Modern mechanical engineering, series A 10 139–48
[12] Ogawa, Yoshida, Yokota 1989 The development of speed control systems for the Savonius wind turbine Modern mechanical engineering, series A 10 60–6
[13] Shishkin N D, Terentyev I S 2015 The evaluation of the main parameters of the combined vertical-axial installations for ships and oil platforms Vestnik of Astrakhan State Technical University. Series: Marine engineering and technologies 2 56–63
[14] Shishkin N D and Ilyin R A 2018 Analysis of aerodynamic parameters and energy efficiency of vertical axis wind turbines Vestnik of Astrakhan State Technical University 1 76–84 DOI: 10.24143/1812-9498-2018-1-76-84
[15] Shishkin N D and Ilyin R A 2018 Ilyin R A and Shishkin N D 2018 Estimation of parameters of vertical axis wind turbines for power plants of small size vessels Vestnik of Astrakhan State Technical University. Series: Marine engineering and technologies 3 93–100 DOI: 10.24143/2073-1574-2018-3-93-100
[16] Kirpichnikova I M, Krivosipitsky V P and Solomin E V 2018 The wind power installations "SRC-Vertical" MANEB Bulletin. The application for Mater. I International scientific-practical Conf. "Resource conservation and renewable energy sources: economy, ecology, application experience", Saint Petersburg, Chita 13 129–34
[17] Shishkin N D and Ilyin R A 2019 Experimental study of parameters of vertical-axial wind-power plants for propeller drives on small ships Vestnik of Astrakhan State Technical University. Series: Marine engineering and technologies 2 93–100 DOI: 10.24143/2073-1574-2019-2-93-100
[18] Shishkin N D, Ilyin R A and Atdaev D I 2019 The Use of Environmentally Friendly Vertical-Axis Wind Power Plants for Nature Reserves and National Parks in Southern Russia Ecology and Industry of Russia 23 43–9 DOI: 10.18412/1816-0395-2019-11-43-49
[19] Abramov A A, Shishkin N D. 2018 The estimation of the vertical-axial wind mills parameters for oil production on the Caspian shelf. The latest technologies for the development of hydrocarbon deposits and ensuring the safety of the Caspian shelf ecosystems: materials of the IX International scientific and practical conference, September 7, 2018 (Astrakhan: publishing house of ASTU) 147–51

[20] Shishkin N D and Ilyin R A 2018 The design and estimation of the parameters of the vertical-axial wind-mill electric generating unit for the self-generated power supply of the objects. Journal of Physics: Conference Series 1111 012055 DOI: 10.1088/1742-6596/1111/1/012055

[21] Shishkin N D and Ilyin R A 2018 Savonius rotors research for the self-generated power supply by land and by sea. Journal of Physics: Conference Series 1111 012056 DOI: 10.1088/1742-6596/1111/1/012056

[22] Shishkin N and Il’in R 2018 Experimental determination of the energy efficiency of rotors of vertical-axis wind turbines for autonomous power supply on land and at sea. MATEC Web of Conferences 245 06016 DOI: 10.1051/matecconf/201824506016

[23] Shishkin N D 2012 The effective use of renewable energy sources for autonomous heat supply of various objects: monograph (Astrakhan: publishing house of ASTU) p 208