Experimental Investigation on the Influence of Overlap Ratio on Savonius Turbines Performance

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Abstract- The paper presents an experimental investigation regarding the influence of the overlap ratio of blades of Savonius wind turbine over its power coefficient and power. Four Savonius wind turbines were fabricated with the overlap ratio of blades of 0.15, 0.20, 0.25 and 0.30. The turbines were subjected to an airflow directed through an open subsonic wind tunnel. With the obtained results were determined, for each rotor, the variation equations of the rotations per minute depending on wind speed. Afterward, the function type and model of power variation curves depending on wind speed were determined. Following tests, it can be concluded that for wind speeds less than 4 m/s is suitable to be used the Savonius turbine with the overlap ratio of 0.15, while for wind speed that exceeds 4 m/s or areas where the wind has a turbulent character, the Savonius turbine with the overlap ratio of 0.30 is recommended.

Keywords Savonius turbine, overlap ratio, tip speed ratio, power coefficient, power.

1. Introduction

Choosing the proper type of turbine and its optimal placement are the most important steps in ensuring the success of an investment in wind energy. To achieve this goal, it is essential to know the basic principles of wind turbines operation [1]. The physics phenomena associated with the wind turbines operation are in the fluid mechanics and aerodynamics field. The air streams are acting the rotor blades of a turbine making it to move - because of either the aerodynamic friction or lifting effect. The movement generated in this way is transmitted directly to mechanical load or to an electric generator depending on the type of the wind turbine [2].

Based on the aerodynamic principles of the wind turbines operation, they can be divided them into two categories: horizontal and vertical rotor wind turbines. The horizontal rotor uses exclusively the aerodynamic lifting effect (called "lift-type rotors"), while the vertical rotor uses the aerodynamics friction effect to create a spinning motion (called "drag-type rotors") - with one exception: Darrieus rotor, which is a lift-type vertical axis wind turbine [3].

Due to the fact that wind turbines with horizontal axis are efficient only in areas with high wind potential where the wind speed exceeds 7 m/s, the wind turbines with vertical axis may represent the future solution for power generation in areas with low air streams speeds (between 2 m/s to 5 m/s) or in areas where the wind has a turbulent character [1,4]. Besides this, the turbines with vertical rotor have the big advantage of generating electricity rapidly because the devices required for orientation on wind direction are removed.

One of the vertical axis turbines which operates on the principle of aerodynamic friction was invented in the twentieth century by the Finnish researcher S.J. Savonius. Two semi-cylindrical blades placed in “S” shape make up the rotor, the concave and the convex side of the rotor being simultaneously under the wind influence [5]. The rotation of the rotor is possible due to different values of the friction coefficient of the two blades during the wind action - the friction coefficient of the concave surface of the blade is greater than that of the convex one. This has a direct influence on the forces acting on the two blades: the force acting on the concave blade is greater than the force acting on the convex blade. Thus, the moment generated by the first force is also greater than the one given by the second force, thereby ensuring the rotation of the vertical axis rotor [2,5]. Because the torque is generated by the difference between the two couples produced by the wind action on the rotor's blades, Savonius turbines have lower power coefficients than wind turbines with propeller rotor, which can achieve a maximum value of 0.593, value known as the "Betz Limit" [4]. Power coefficients of Savonius turbines have values between 0.20 and 0.30, which means that vertical axis turbine will use only 20% to 30% of the energy received from the wind [3,6-9]. However, after practical experiments in aerodynamic tunnel, it was demonstrated that Savonius turbines could reach values of power coefficient up to 0.31 and even to 0.35 for some prototypes tested under the air streams. These values make the Savonius rotor significantly interesting in converting wind energy into electricity [4].

The power coefficient of Savonius turbines can be improved by different methods, in order to approach it as much as possible to the maximum theoretically values. These improvement methods are: choosing an optimal configuration of vertical axis rotors [10,11], determining the optimal overlap ratio of rotors blades [12,13], establishing the proper floors number of the rotor blades [14-16] and using the concentrators [17].

The purpose of this paper is to determine the power coefficient and the mechanical power supplied by Savonius turbines by using one of the above mentioned performance improvement methods, namely the determination of the optimal overlap ratio of rotors blades. The aim of the experimental tests was to link the vertical axis wind turbines rotation per minute (*rpm*) at different wind speeds to the overlap ratio of rotor blades [12,13,18,19]. Afterwards, the tip speed ratio λ was determined for each rotor; this parameter is required for the determination of the power coefficient needed in the calculation of the mechanical power that the rotor can provide to the spindle.

2. Materials and Methods

2.1 Materials

For the experiments, were fabricated in-house four Savonius rotors with semi-cylindrical blades [20,21]. The rotors have equal areas, the same aspect ratio, but different overlap ratio (OR) of blades (e/D) with values of 0.15, 0.20, 0.25 and 0.30. Constructive shape and drawing with the operation principle of a Savonius turbine are presented in Figure 1, respectively Figure 2. In Table 1 are shown the dimensional characteristics of each made-up turbine.

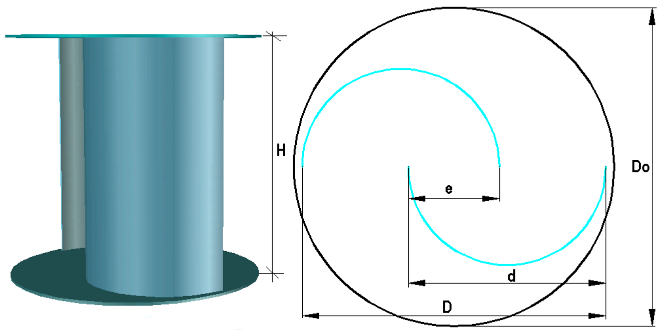

Fig 1. Savonius turbine constructive shape used in experiments

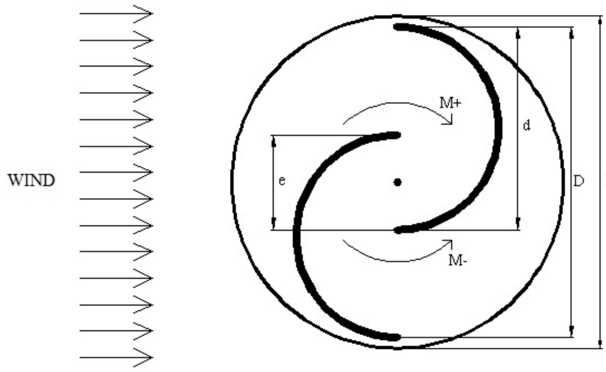

Fig 2. Scheme with operation principle of Savonius turbine

Table 1. Dimensional characteristics of made-up Savonius turbines

Dimensional characteristics	OR 0.15	OR 0.20	OR 0.25	OR 0.30
Rotor diameter, D [cm]	18 cm	18 cm	18 cm	18 cm
Blade diameter, d [cm]	10.4 cm	10.8 cm	11.3 cm	11.7 cm
Rotor height, H [cm]	18 cm	18 cm	18 cm	18 cm
Endplate diameter, D_0 [cm]	19 cm	19 cm	19 cm	19 cm
Overlap distance, e [cm]	2.7 cm	3.6 cm	4.5 cm	5.4 cm
Overlap ratio, e/D	0.15	0.20	0.25	0.30

The material used for the experimental wind turbines rotor blades was plastic. The end plates and the other parts of the rotor were made of komatex. For blade assembly with the end plates and with the rotor shaft was used a silicone-based adhesive. The rotor built in this way was mounted on a metal frame by means of thrust bearings [10,22].

The wind turbines were tested in front of an open subsonic wind tunnel (see Fig. 3) that blows air, simulating wind speeds from a minimum value up to 7 m/s. The wind tunnel [22] is composed of three different sections. The inlet section is imposed by the axial fan diameter, Ø400 mm, with a length of 1000 mm. The second section makes the transition from the circular to square section; its length is of 500 mm. The outlet section of the wind tunnel requires a size of 1.2-1.5 times higher than the rotor (which has a diameter of 180 mm and a height of 180 mm). Thus, the outlet section has a square size of 300x300 mm and a length of 1500 mm. All three sections are made of galvanized steel sheet.

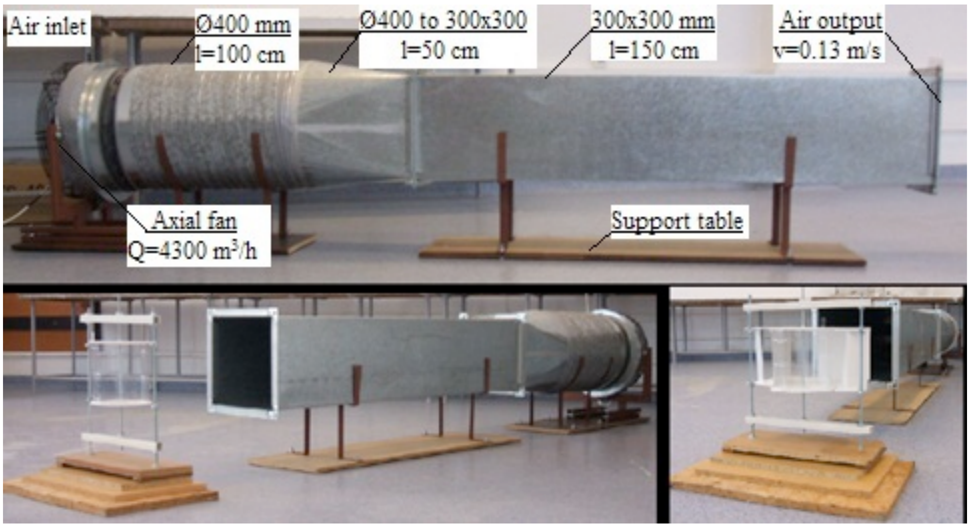

Fig 3. Open-circuit subsonic wind tunnel [20]

For an accurate and rapid measurement of the airflow velocity given by the wind tunnel a high precision anemometer with propeller, AM50, was used. The anemometer is capable of measuring airflow speed between 0 and 45 m/s with an accuracy of ±3%. The rotation speed of the rotor depends on the speed of the airflow they are exposed to. Therefore, its recording was performed with a portable digital tachometer, Voltcraft DT-10L. The digital tachometer has a measuring range from 2 to 99,999 rotation per minute with an accuracy of ±0.05%. The recommended measurement distance is between 5 and 50 cm. In order to measure the angular velocity a torque meter, PCE-TM 80, was used. This torque meter records values from 0 to 147 (N*cm) and has an accuracy of ±1.5%.

For better measurements' accuracy, the anemometer was placed at the outcome of the aerodynamic tunnel. The preliminary determinations demonstrated that a distance of about 3 to 5 equivalent diameters of the wind turbines from the wind tunnel outlet section was the best solution in obtaining a laminar airflow regime. The rotor speed of the spinning was monitored from a distance of approximately 30 to 40 cm using the digital tachometer. The external sensor of the torque meter was placed on the rotor shaft.

The operational scheme of the experimental stand is presented in Figure 4.

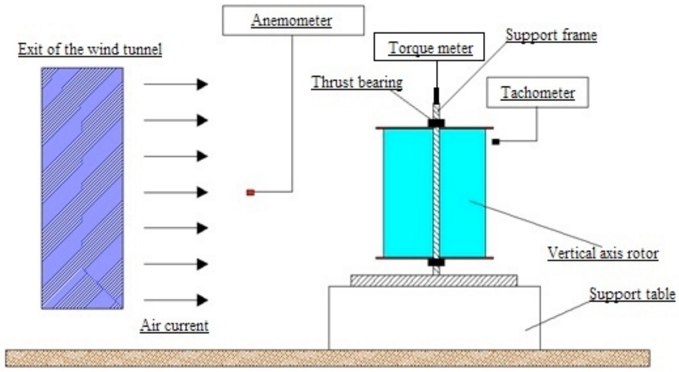

Fig 4. The operation scheme of the experimental set-up

2.2 Mathematical equations

The mechanical power, *P*, which may be absorbed from the air streams by means of a wind rotor, can be expressed by the following equation [23]:

$$P = \frac{1}{2}\rho A v^3 C_p \quad (1)$$

where: ρ – air density [kg/m^3]; A – rotor area [m^2]; v – wind speed [m/s]; C_p – power coefficient.

The calculation of the rotor area for Savonius rotors is relatively simple because it can be assimilated with the area of a rectangle defined by the height H and rotor diameter D, as it can be seen in the next relationship [3,23]:

$$A = D \cdot H \quad (2)$$

The rotor's power coefficient, C_p, expresses the amount of energy that can be extracted from the available energy from the wind by using this rotor. It has variable values depending on the tip speed ratio (λ) and coefficient of torque (C_t) of the rotor [4,24] :

$$C_p = \lambda \cdot C_t \tag{3}$$

The tip speed ratio is calculated with the formula [2,14]:

$$\lambda = \frac{\omega R}{v} \tag{4}$$

where: ω - angular speed [rad/s]; R – rotor radius [m]; v – wind speed [m/s].

The coefficient of torque is determined with the equation [3,14]:

$$C_t = \frac{2T}{\rho \cdot v^2 \cdot A \cdot R} \tag{5}$$

where: T - torque [N*m].

Because the parameter rotations per minute of the turbines' rotor is very important in establishing which type of the considered OR is better depending on the wind speed, the CurveExpert software was used to highlight the trends and equations of the characteristic curves of the fourth studied Savonius turbines.

3. Results and discussions

In order to establish the influence of the overlap ratio (OR) on the performance of the studied Savonius turbines, the experiments concentrated on the important parameters already specified: rotations per minute, tip speed ratio, coefficient of torque, power coefficient and power. All of them are depending on the wind speed, the main factor.

Table 2 summarises the rotation per minute variations (rpm) with the wind speed for each studied turbine.

Tabel 2. Rpm maximum and minimum values depending on wind speed for all four types of Savonius turbine

v [m/s]	OR 0.15		OR 0.20		OR 0.25		OR 0.30	
	rpm		rpm		rpm		rpm	
	max	min	max	min	max	min	max	min
1	96	84	84	79	75	65	68	62
2	283	277	283	273	211	209	200	180
3	377	373	375	364	348	332	305	295
4	460	450	406	400	413	407	453	447
5	476	474	507	498	575	575	615	605
6	495	485	540	530	622	618	679	671
7	530	520	550	540	615	605	651	649

The measurements presented in table 2 shows a rapid increase of the *rpm* of the rotor with the increase of the wind speed up to 5.5÷6 m/s, followed by a decrease of the rising rate due to turbulences and vortex effects that occur because of the rotor blades rotation. From the same table, it can be observed that the Savonius turbine with OR 0.15 has the highest values of the *rpm* of all four turbines tested at 1 m/s wind speed. This happens due to the active surface of the rotor which is larger than the other three turbines and the moment acting on the convex blade is lowest due to a smaller blade diameter. The first that starts rotating at 0.4 m/s wind speed is the rotor with overlap ratio (OR) of 0.30, but at 1 m/s speed it shows the lowest values of the all *rpms*. The highest values of the *rpm* are recorded for OR 0.30 at 6 m/s wind speed, followed by OR 0.25 for the same wind speed. In case of higher wind speeds, the rotor with a smaller active surface of the rotor blade showed a higher value of the *rpm* due to a greater overlap distance. The moment acting on convex blade is low again because a small part of the wind that acts on the concave blade passes thru the gap formed by the overlap distance and reduces negative moment.

It can also be noticed that for the turbines with the overlap ratio of 0.15 and 0.20, the *rpm* values have a linear increase from the minimum to the maximum speed. For the other two types of turbines, OR 0.25 and OR 0.30, the *rpm* values point out an increase from the minimum speed until reaching the speed of 6 m/s, after which, due to turbulence and vortex effect, it is a slight decrease.

Using data obtained from tests, it results a comparative graph of *rpm-v* curves (at averages values of *rpm*) for all Savonius turbines used in experiments, as shown in Figure 5.

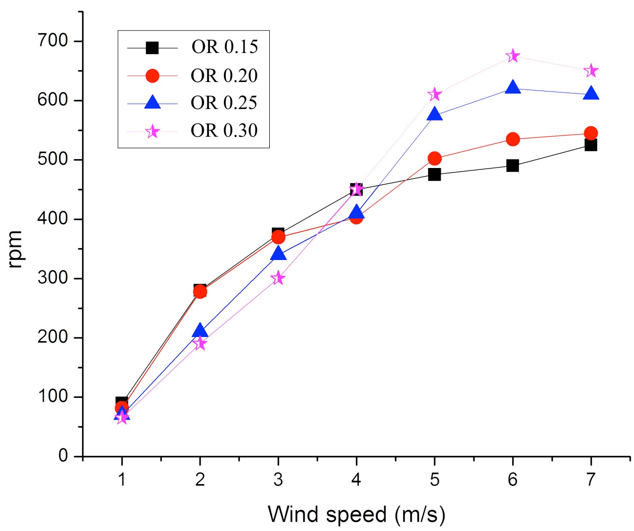

Fig 5. Comparative graph of rpm-v curves (at averages values of rpm) for all tested Savonius turbines

Analysing the comparative graph, it can be observed that for wind speed between 1 and 4 m/s the rotor with OR 0.15 has the best performance. For higher speeds of the air flow, OR 0.30 has the best results.

In table 3 are presented the torque values recorded during experiments for *rpm* average values of each studied turbine.

Tabel 3. Torque's medium values recorded for all four types of Savonius turbine

v [m/s]	T [N*cm]			
	OR 0.15	OR 0.20	OR 0.25	OR 0.30
1	0.06	0.06	0.07	0.07
2	0.13	0.14	0.21	0.23
3	0.38	0.36	0.43	0.51
4	0.81	0.90	0.88	0.81
5	1.47	1.41	1.19	1.12
6	2.38	2.25	1.98	1.82
7	3.34	3.34	3.09	2.95

From the above table, it can be seen that at a wind speed of 1 m/s, the rotor with the OR 0.30 has the highest value of torque for all tested turbines. On wind speed of 7 m/s, the rotor with OR 0.15 presents the greatest value of torque for all turbines. By comparing the values from the above table with the values summarised in table 2, it can be observed that the torque is inversely proportional to the rotations per minute of each turbine.

Because the turbine with OR 0.30 is the first one that started to rotate during the experiments and throughout the range of wind speed from 1 to 7 m/s and presented the greatest rate of rotation of the rotor, its characteristic curve is presented in Figure 6.

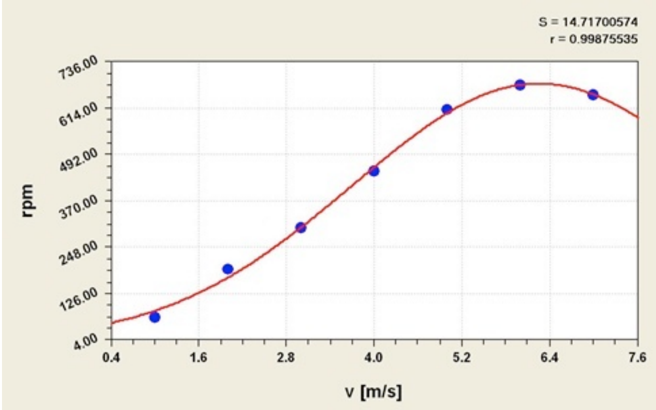

Fig 6. Characteristic curve of rpm-v of the Savonius turbine with OR 0.30

A very important aspect that should be known about the functioning of vertical axis turbines are the variation equations of rotor rotations per minute depending on wind speed. Table 4 presents these characteristic functions after which the rotor's *rpm* varies with the wind speed.

Tabel 4. Equations of characteristic curves *rpm-v* of operating turbines

Turbine type	Function type	Function	Coefficients	Standard error Correlation coefficient
OR 0.15	Polynomial degree 3	$rpm = a + bv + cv^2 + dv^3$	a=-184.28 b=328.968 c=-56.845 d=3.4722	E=7.7022 C=0.99938
OR 0.20	Polynomial degree 4	$rpm = a + bv + cv^2 + dv^3 + ev^4$	a=-358.714 b=617.523 c=-209.25 d=33.813 e=-1.9848	E=19.1714 C=0.99778
OR 0.25	Polynomial degree 3	$rpm = a + bv + cv^2 + dv^3$	a=-12.857 b=69.761 c=23.2738 d=-2.9166	E=30.0231 C=0.99501
OR 0.30	Gauss model	$rpm = ae^{\frac{-(v-b)^2}{2c^2}}$	a=679.293 b=6.2478 c=2.5504	E=14.717 C=0.99875

The standard error, correlation coefficient and the finest approach of the curve trend to experimental data are the main factors in choosing the optimum equation, respectively the optimum type of the Savonius turbine. The standard error has to be as small as possible; the correlation coefficient must have a value as close to 1. Thus, it results that the Savonius turbine with OR 0.15 has the lowest standard error and the correlation factor is the nearest to 1 (according to the data from Table 3).

Following these tests and analyses, it can be concluded that the optimum overlap ratio of blades is 0.15 for wind speeds less than 4 m/s. For wind speeds exceeding 4 m/s, the optimal overlap ratio of blades is 0.30. In addition, this is the first rotor that starts rotating at wind speeds of about 0.4 m/s and could begin to produce power from the wind speed close to 1 m/s, depending on the type of the chosen electric generator.

Knowing the spinning speed of the rotor for any value of wind speed is very useful in choosing the proper electric generator that will equip the wind turbine, even if it is directly connected to the rotor shaft or coupled to the rotor through a gearbox or speed multiplier. In this way, the performance of the turbine-generator tandem is high, ensuring a maximizing exploitation of the efficiency of wind energy [22, 25-27].

To establish which Savonius turbine produces the greatest mechanical power available at the rotor shaft, the power coefficient of each tested turbine is needed to be determined. As it can be seen from equation (3), the power coefficient is the product between tip speed ratio and coefficient of torque.

The tip speed ratio (λ) of the turbines was calculated with relation (4), at different wind speeds. Based on the values obtained for λ, it was made a comparative graph (see Fig. 7), where can be observed the variation curves of each turbine.

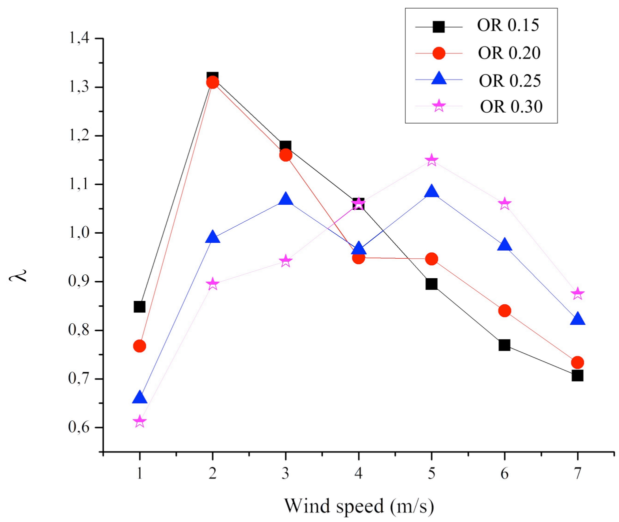

Fig 7. The comparative graph of the λ-v variation curves for tested turbines

From the above figure, it can be observed that for wind speeds between 1 and 3 m/s, the rotors with a smaller overlap ratio (i.e. 0.15 and 0.20) presents the highest tip speed ratio. This happened because these two rotors have a larger surface of the blades submitted to the wind action, in comparison with the other two rotors (0.25 and 0.30). Therefore, the force acting on the concave blade is higher and produce a higher tip speed ratio for OR 0.15 and 0.20. At the wind speed of 4 m/s, the tip speed ratio of the four rotors is in the range of 0.9 and 1.05. For wind speeds between 5 and 7 m/s, the rotors with the overlap ratio of 0.30 and 0.25 presents the higher tip speed ratio compare to the other two rotors.

Based on the values of tip speed ratio λ, calculated with equation (4) and on the coefficient of torque determined with formula (5), the power coefficient C_p it is determined for each turbine. The values of the power coefficient are presented in Table 5.

Tabel 5. The values of the power coefficient depending on the wind speed for each tested turbine

v	C_p

[m/s]	OR 0.15	OR 0.20	OR 0.25	OR 0.30
1	0.295	0.285	0.26	0.25
2	0.25	0.255	0.29	0.295
3	0.28	0.265	0.29	0.30
4	0.30	0.30	0.30	0.30
5	0.295	0.30	0.29	0.29
6	0.285	0.295	0.30	0.30
7	0.27	0.28	0.29	0.295

Analyzing the values obtained for the power coefficient of each tested turbine, it can be observed that, at 4 m/s wind speed, the power coefficient value is equal to its theoretical value (0.30) for all turbines. The average of power coefficient per turbine, from minimum speed to maximum, shows that the Savonius rotor with OR 0.30 presents the highest value (0.29).

Depending on the values obtained for the power coefficient, it can be calculated the mechanical power available at the rotor shaft for each rotor, according to relation (1). In Figure 8 is presented a comparison between the mechanical power available at the rotor shaft delivered by each rotor used in the experiment at different wind speeds.

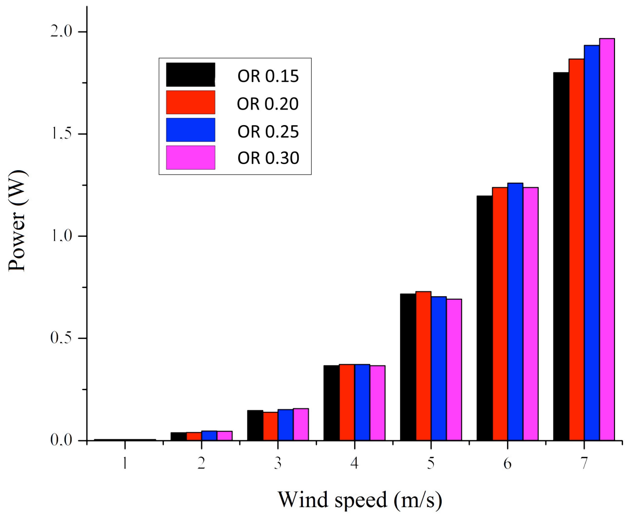

Fig 8. The power delivered by each rotor tested at different wind speeds

From the graphical representation, it can be noticed that for the wind speed of 1 m/s the Savonius turbines with the OR 0.15 and OR 0.20 delivers a greater power than the other two turbines, but the differences are very small. A slight significant difference it can be observed at 3 m/s wind speed, were the OR 0.30 has a light increase compared to the other three. At 4 m/s wind speed, the values of the mechanical power available at the rotor shaft delivered by each rotor are approximately equal. For the wind speed of 5 m/s the situation is similar to the one of 1 m/s wind speed. At the maximum wind speed used in tests, the turbine with OR 0.30 delivers the greatest amount of power (about 2 W).

The power extracted from the wind with a wind turbine is a typical function depending on the cube of the wind speed (as it results from the analysis of the power definition equation (1)). In these circumstances, it is very interesting to see if the relationship of the extracted power from the wind and the variation curves of the vertical axis wind turbines used in the experiment are changing and how. To achieve this comparison, the values of the power depending on wind speed, as shown in Figure 8, were processed by *CurveExpert.* Afterwards, it was determined the type and model of the power variation curves depending on wind speed. Since Savonius turbine with OR 0.30 has the highest average power coefficient and delivers the greatest amount of power, in Figure 9 it is shown the processed shape of the its *P-v* curve. Table 6 presents the function type and the parameters of *P-v* curves for all studied vertical axis turbines.

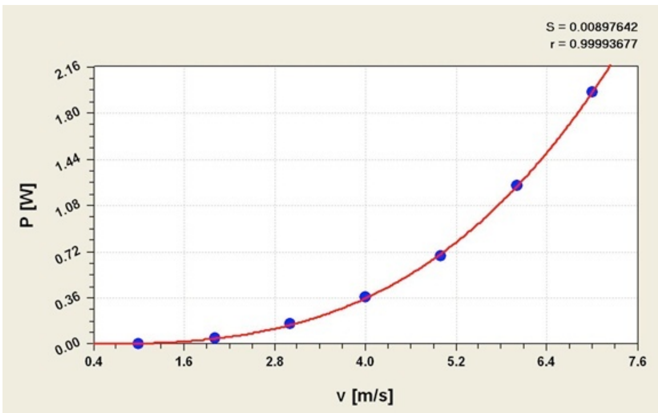

Fig 9. The P-v characteristic curve of Savonius turbine with OR 0.30

Tabel 6. Equations of characteristic curves *P-v* of operating turbines

Turbine type	Function type	Function	Coefficients	Standard error Correlation coefficient
OR 0.15	Polynomial degree 4	$P = a + bv + cv^2 + dv^3 + ev^4$	a=0.00152 b=0.01027 c=-0.01715 d=0.01186 e=-0.000625	E=0.00100 C=0.99999

OR 0.20	MMF model	$P = \frac{ab + cv^d}{b + v^d}$	a=-0.000414 b=1990.18 c=7.95499 d=3.2956	E=0.00566 C=0.99998
OR 0.25	Gompertz relationship	$P = ae^{-e^{b-cv}}$	a=10.4004 b=2.13593 c=0.23089	E=0.01216 C=0.99990
OR 0.30	Power function	$P = av^b$	a=0.00534 b=3.0362	E=0.00897 C=0.99993

From table 6, it can be observed that only for the Savonius turbine with OR 0.30, the defining relation of the *P-v* curve remains a power type one, but even in this case, the power of the wind speed is 3.03. For other turbines studied, the relation defining the *P-v* characteristic curve is much different from a power function.

4. Conclusions

Due to simple design and to low production and exploitation costs, Savonius turbines have become increasingly interesting for the production of electricity through wind energy conversion. Therefore, these turbines are achievable especially in the case of residential and commercial small installations with limited powers, which may contribute to decentralization of national energy systems.

Following this research, the best results regarding the power coefficient were obtained for the Savonius wind turbine with OR 0.30 with an average value of 0.29. These assumptions remain valid even after analysing the amount of energy produced by each rotor. Savonius rotors with OR 0.15 and OR 0.30 generates, in the wind speed range of 0÷7 m/s, an average power of 0.61 W, respectively 0.64 W. The maximum mechanical power available at each rotor, calculated at 7 m/s wind speed, is 1.80 W for OR 0.15, respectively 1.97 W for OR 0.30, representing a fraction of 0.25 and 0.29 of the total available power in the wind, which is about 6.67 W.

From the analysis of the equations obtained for the P-v characteristic curves it is observed that only in the case of Savonius wind turbine with the overlap ratio of blades 0.30 the defining relation is a power type one.

Therefore, it is very important to know in detail the wind characteristics in the area in which will operate the turbines, because in the case of areas in which there are estimated average annual speeds of wind that doesn't exceed 4 m/s, it is indicated to use Savonius turbines with the OR 0.15. In the case of an average annual speeds higher than 4 m/s or areas where the wind has a turbulent character, Savonius turbine with the OR 0.30 are recommended, to maximize the electricity production.

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