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THE INFLUENCE OF THE NUMBER OF SEMI-CYCINDRICAL CUPS ON THE BEHAVIOR OF AN EXPERIMENTAL MODEL OF VERTICAL AXIS WIND TURBINE AT LOW WIND SPEED AND NO LOAD

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ABSTRACT

The work is based on experiments made in the wind tunnel on experimental models of Savonius type wind turbines with blades in the shape of a semi-cylindrical cup. The number of blades changes: 2, 3, 4, 5 and 6. The experimental model allows the addition / removal of blades in the form of a semi-cylindrical cup followed by static balancing. The wind tunnel used has the measuring area 0.5m x0.5m and the length of 1.25 m and the experimental models have the interception surface at a maximum value of 10% of the cross-sectional area of the wind tunnel (diameter 158mm and height 158 mm). The experiments were performed at wind speeds between 0...9.7 m/s between peaks and no (mechanical and / or electrical) loads. The results confirm the influence of the number of semi-cylindrical cups on the rotational speed and other factors over experimental model of Savonius type turbines in no load conditions.

KEYWORDS: Savonius, S-rotor, rotation speed, semi-cylindrical cups

1. Introduction

Vertical axis wind turbines (VAWT) have some features attractive enough for use in hybrid lighting. Although the efficiency is low (maximum 14.81%) [1] the constructive simplicity, the independence of the wind direction, the high torque are the basic characteristics that today are corroborated with the increase of the luminous efficiency of the LED lighting systems from 100lm/W to recent 200 lm/W (Haitz's law) [2].

That is why the design of the vertical axis wind system must be maximized by finding the most accurate aerodynamic structure, shape and dimensions [3-5].

From the start, the main disadvantage of the proposed wind turbine model is the variability of the output speed and the useful torque with the wind speed (Fig. 1). The aim is about the intrinsic variability of the wind converter [6, 7]. Variability is given by the wind. For the proposed location (Galați, Romania) the values medium a maximum of average wind is showing in Fig. 2. It has values: maximum 61 Km/h (16.9 m/s) and average 20 km/h (5.55 m/s).

Therefore, the use of VAWTs is indicated because there is an average value of the wind speed in their working range and the behavior at a maximum speed of over 15 m/s must be solved mechanically.

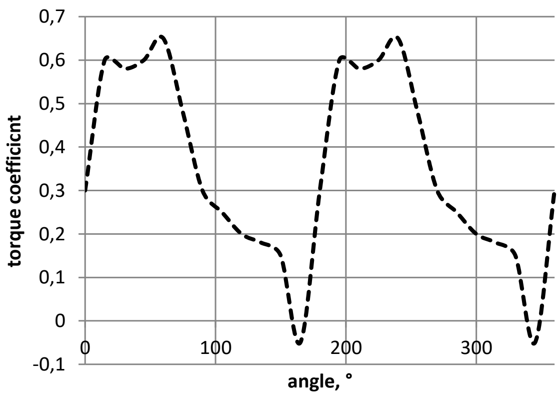

***Fig. 1.** Axis torque variation for SWT* [6]

The work is based on experiments made in the wind tunnel on experimental models of Savonius type wind turbines with blades in the shape of a semi-cylindrical cup. The number of blades changes: 2, 3, 4, 5 and 6. An EMs of maximum dimensions is made for the wind tunnel (158 x158 mm), removable and to which the blades can be added or removed. EM consists of 2 base plates of 0.4 mm Al sheet. 2, 3 4, 5 or 6 blades can be attached (Al sheet with a thickness of 0.4 mm). This is possible by designing the experimental model with removable semi-cylindrical cups. EM is fixed on a frame with two sleepers: the lower crossbar has a tip bearing in the middle and the speed-reading system with 60-slot disc and IR window optocoupler with window.

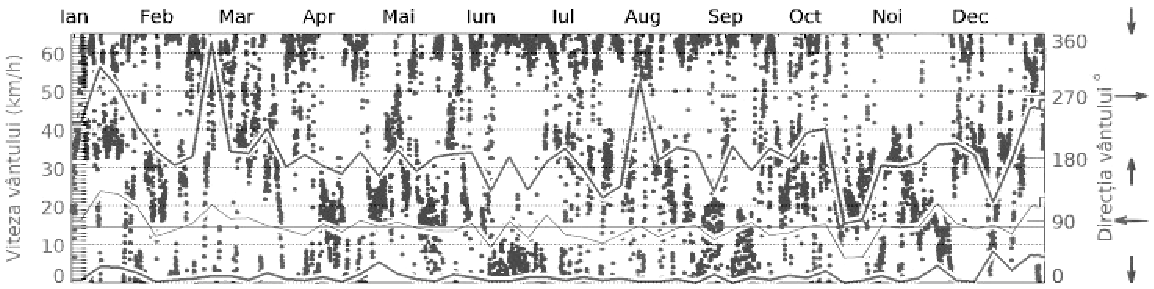

Fig. 2. *History of maximum, minimum and average values for the city of Galati for 2019* [8]

Notations:

u - tip blade speed, m/s;

$\dot{V}$ - volumic debit m^3/h;

$\dot{m}$ - mass debit, kg/m^3;

A - swept aria, m^2;

p - wind power, W;

ρ - air density, kg/m^3;

n - rotation speed, rpm;

C_D - drag coefficient;

λ - specific speed.

Abbreviations

VAWT - Vertical Axis Wind Turbine;

HAWT - Horizontal Axis Wind Turbine;

EM - Experimental Model;

LED - Light Emitting Diode;

Pb - Lead (lead Battery);

Cd-Ni - Cadmium-Nickel (Cadmium-Nickel battery;

NiMh - Nickel metal hydride battery;

LiPo - Lithium Polymer Battery;

S2CNL - Savonius 2 Cups No Load;

S3CNL - Savonius 3 Cups No Load;

S4CNL - Savonius 4 Cups No Load;

S5CNL - Savonius 5 Cups No Load;

S6CNL - Savonius 6 Cups No Load.

The upper cross member has two working possibilities. A bearing similar to the one at the bottom, when practically the system works between the tips with a minimum mechanical friction load. The second variant is with the connection of a three-phase generator 3V...24V, a case in which the system has a mechanical load and to which a variable electric (resistive) load can be connected, in order to observe the influence of the electric load on the wind turbine performance. The electrical efficiency of the EM for the considered electric load can be calculated.

The system is equipped with a data acquisition system which is purchased with an anemometer speed, model speed, load current and voltage at the generator (rectified and filtered). The system calculates the wind speed, wind power on the interception area, power on the electric load and the electrical efficiency of the wind turbine (which also includes the mechanical efficiency).

It represents graphically the quantities purchased for wind speeds between 0...9.5 m/s, with fixed steps of 0.5 m/s. The adjustment of the wind speed is done manually and therefore a time is maintained on each gear to stabilize the operation of the wind tunnel and the EM of the wind turbine.

Wind energy is pure kinetic energy and can be partially transformed into mechanical work [1, 2].

$$E = 0{,}5mv^2 \tag{1}$$

The volume flow over the swept area is:

$$\dot{V} = Av \tag{2}$$

And the mass flow is:

$$\dot{m} = \rho Av \tag{3}$$

The power of wind is depending by wind speed (v), air density (ρ) and swept area (A):

$$P = 0{,}5\rho Av^3 \tag{4}$$

For the VAWT, the Betz limit is (14.81%) [1].

The influence of air density over wind power is:

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$$\rho_a = \frac{353.049}{T} e^{-0,034\frac{z}{T}} \quad (5)$$

Pushing force is for an object fixed on the surface a placed in the path of an air flow:

$$\frac{F}{A} = \frac{1}{2} p v^2 C_D \quad (6)$$

C_D is defined as an important parameter when it comes to wind resistance.

The power extracted from a wind power by a VAWT Savonius type is depending by Drag force is:

$$P = \frac{1}{2} p v^3 C_D A \quad (7)$$

In case of wind turbines, the relative speed is:

$$v_r = v - u \quad (8)$$

The specific power is:

$$\frac{P}{A} = \frac{1}{2}(v-u)^2 C_D u \quad (9)$$

The VAWT extract power at axis by the relation:

$$P = C_p \rho_a H v_i^3 \quad (10)$$

The axis torque is as follows:

$$P = C_m \rho_a R^2 H v_i^2 \quad (11)$$

The power conversion efficiency is defined by the extracted power related to wind power.

$$\eta = \frac{P}{P_v} = \frac{\frac{1}{2}\rho(v-u)^2 C_D u A}{\frac{1}{2}\rho A v^3} \quad (12)$$

$$\eta = \frac{(v-u)^2 C_D u}{v^3} \quad (13)$$

Experimental Models (EMs) were made of 0.4 mm thick aluminum sheet with dimensions of H = 158 mm and D = 158 mm.

The interception surface (swept area) is variable with the angular position of the cups shown in Fig. 1.

With the increase of the number of cups swept area approaches the maximum value which is 10% of the area of the measuring section of the wind tunnel

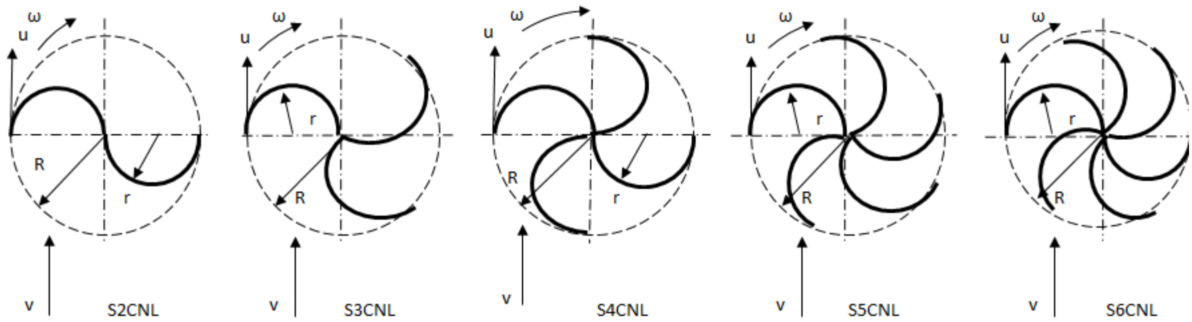

***Fig. 1.** cross sections through the experimental models used*

Table 1

no.	experimental model	n	m	A_s	
				min	max
m.u.		-	kg	m^2	m^2
1	S2C	2	0.092	0.008	0.025
2	S3C	3	0.117	0.02	0.025
3	S4C	4	0.141	0.02	0.025
4	S5C	5	0.166	0.023	0.025
5	S6C	6	0.191	0.023	0.025

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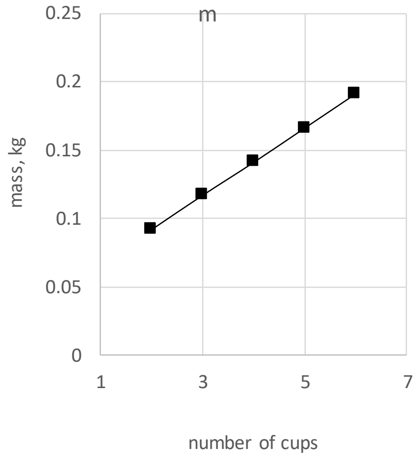

Fig. 3. *The variation of the mass of the experimental models with the number of cups*

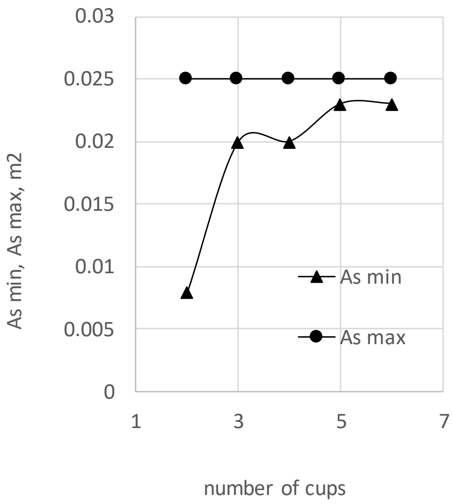

Fig. 4. *The minimum and maximum swept area variation with the number of EM cups*

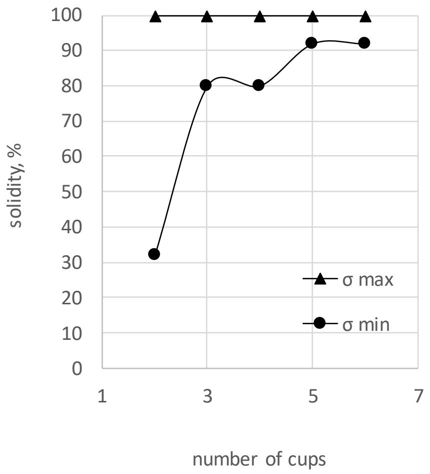

Fig. 5. *The variation of the solidity of the experimental models with the number of cups*

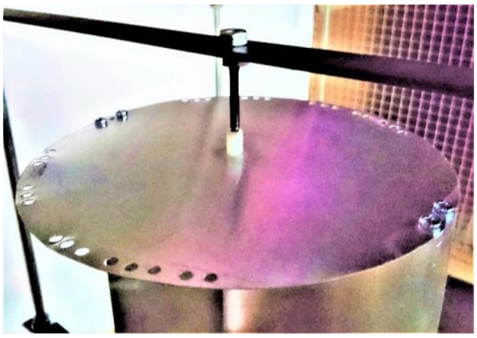

Fig. 6. *Detail regarding the upper bearing*

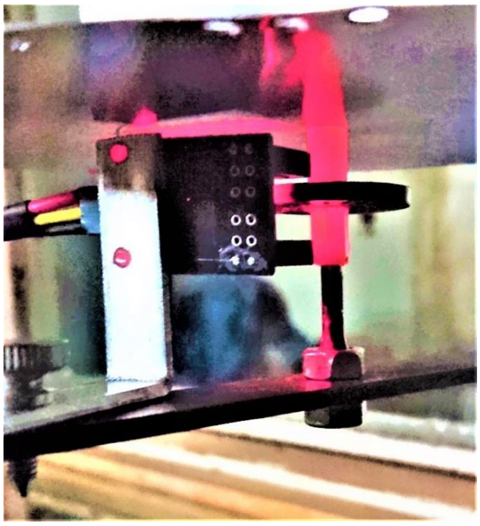

Fig. 7. *Detail of lower bearing and rotary speed transducer*

Fig. 8. *Experimental model with 2 semi-cylindrical cups (S2CNL) fixed on the test frame*

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Fig. 9. *Experimental model with 3 semi-cylindrical cups (S3CNL) fixed on the test frame*

Fig. 10. *Experimental model with 4 semi-cylindrical cups (S4CNL) fixed on the test frame*

Fig. 12. *Experimental model with 6 semi-cylindrical cups (S6CNL) fixed on the test frame*

2. Experiments

The experiments were performed from the maximum wind speed to the minimum, so that the stopping speed of the experimental model is mentioned. A further study will also address the starting speed of experimental models and the differences between the stopping speed and the starting speed.

The experiments were performed in the conditions of the lowest mechanical friction in the bearings, using a tribological system steel tip and plastic bearing and adequate lubrication.

The experiments were developed on a full-factorial matrix. 5 experimental models of vertical axis wind turbines with 2, 3, 4, 5 and 6 semi-cylindrical buckets (Fig. 6....10) and coded S2CNL, S3CNL, S4NL, S5CNL and S6CNL were used. For each, 14 speed measurements were made at 50 s intervals to stabilize the air flow regime.

The experiments for determining the influence of the number of blades on the rotational speed when operating without load (idling) are shown in the diagrams in Fig. 11 to Fig. 15.

The wind speed changes by progressively decreasing from the maximum value to zero time in which both the wind speed and the rotational speed of the experimental EM model are recorded. The experiment is repeated for all five experimental models and the results are shown in the diagrams mentioned.

The diagrams recorded with the variation of the rotational speed of the EM with the progressive decrease of the wind speed show that the EMs behave differently in the range of wind speeds achieved in the wind tunnel. Thus, the maximum rotation speed is approximately between 6.7 m/s and 7.7 m/s. the rotation of the models is done at values of wind speed between 1.9 m/s and 4 m/s.

The experimental 2-bucket model (S2CNL) reaches the highest rotational speed at almost 800 rpm, has a continuous decrease in rotational speed with wind speed and stops rotation at just over 4 m/s.

S2CNL has the lowest mass, has a large variation of the torque with the angle of rotation and wind speed (ref CN) and the rotation stops abruptly at bm values per 4 m/s of wind speed.

The experimental 3-bucket model (S3CNL) has a proportional variation of the rotational speed at high wind speeds. At wind speeds of approx. 6 m/s has a local maximum rotational speed and stops from rated at 3.5 m/s.

The experimental model with 4 semi-cylindrical buckets (S4CNL) has a linear range of decreasing rotational speed as follows: at the maximum wind speed used approx. 670 rpm and slowly decreases to approx. 625 rpm when the wind speed drops to 7 m/s.

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below this speed the experimental model has a rapid decrease in speed and stops at 3.75 m/s.

The experimental model with 5 buckets (S5CNL) tested without loading, has two operating areas: one with constant rotation speed and approx. 670 rpm, for wind speeds from 9.7 m/s to 7 m/s and then a sudden drop and stop at 3.75 m/s wind speed.

The experimental 6-bucket model (S6CNL) also tested without loading has a behavior similar to that of the S5CNL has two operating areas: one with constant rotational speed and approx. 670 rpm, for wind speeds from 9.7 m/s to 7 m/s and then a sudden drop and stopping at 1.25 m/s wind speed.

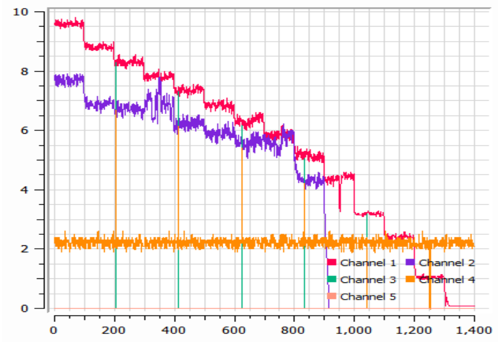

Fig. 13. *Variation of the rotational speed of the experimental model S2CNL with wind speed*

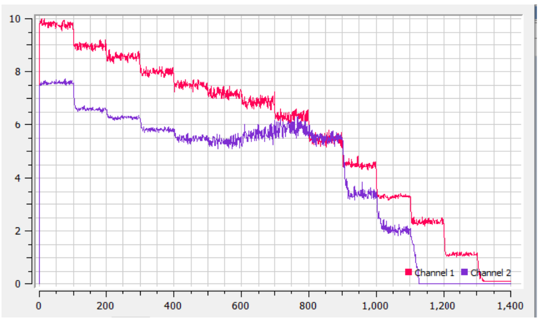

Fig. 14. *Variation of the rotational speed of the experimental model S3CNL with wind speed*

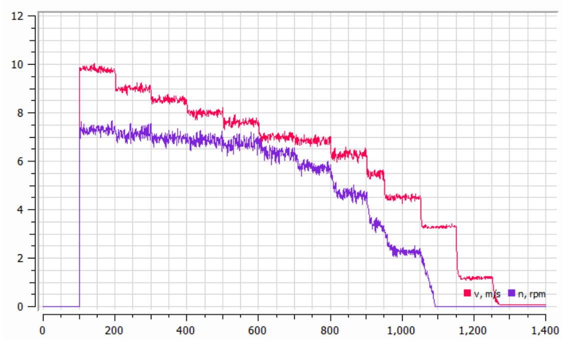

Fig. 15. *Variation of the rotational speed of the experimental model S4CNL with wind speed*

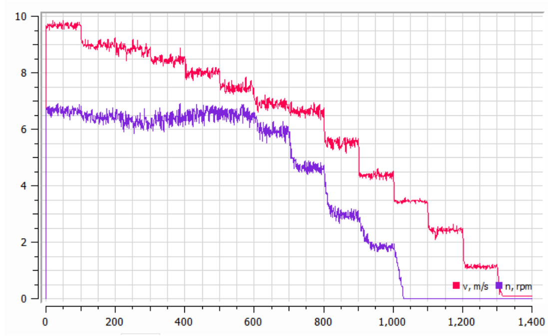

Fig. 16. *Variation of the rotational speed of the experimental model S5CNL with wind speed*

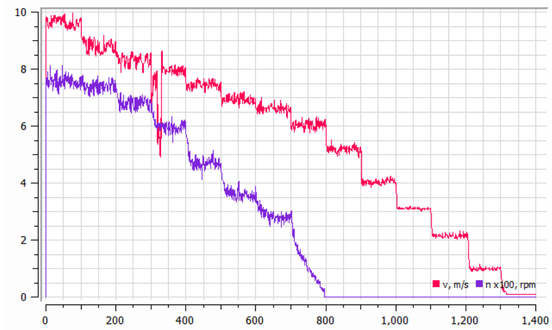

Fig. 17. *Variation of the rotational speed of the experimental model S6CNL with wind speed*

3. Results

Based on the measurements are shown in Fig. 17 the variation of the rotation speed of the experimental models with the wind speed. The stopping speed of the six EMs is between 2 and 4 m/s and the maximum rotation speed in the range of 650-750 rpm. The variation curves have an approximately linear area after which they tend towards a maximum value.

The analysis of the influence of wind speed on the specific speed is shown in Fig. 17 and in this case the curves are grouped in the form of a band in the diagram. EMs has the best behavior with 3 semi-cylindrical cups (S3CNL) which has the best sensitivity to wind speed and the largest λ of about 0.8 at about 5.5 m/s Compared to other models has the largest λ (with small exceptions).

From the point of view of the aerodynamics of the components of the mentioned EM, it is important to reach the highest possible values of the Reynolds number. The length of the semi-cylindrical blade in the section is considered the flow length. The variation of the Re number with the wind speed is shown in Fig. 18. The different composition of the three-bucket model (S3CNL) is observed which does not reach more than 30000. The other experimental models behave similarly and the results form a band

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that at 10 m/s speed of the wind reaches the Re number over 100000. The wind power has a variation with the third power of the wind speed which is seen in Fig. 19.

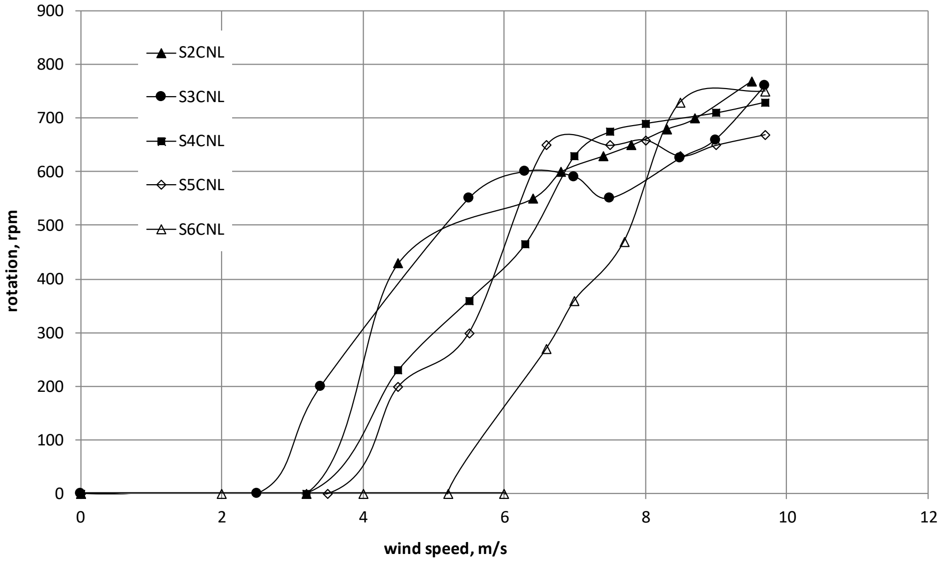

Fig. 18. *Variation of the rotation speed of the experimental models (EM) with the wind speed*

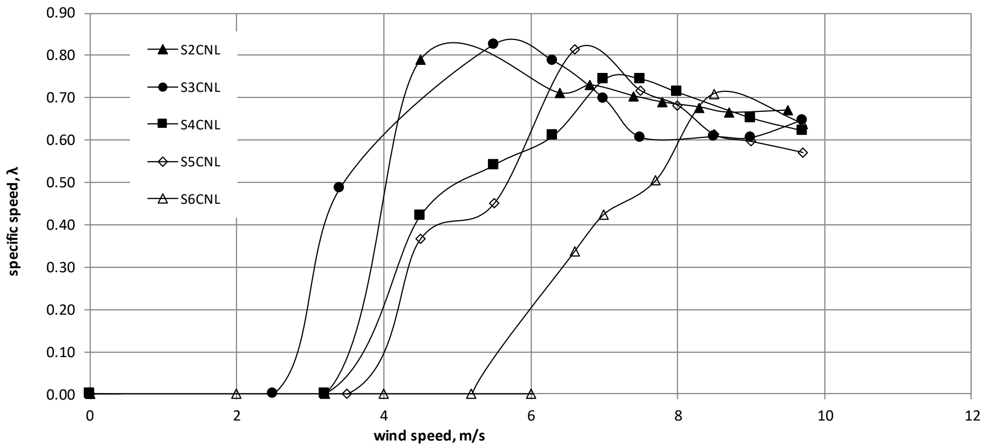

Fig. 19. *Influence of wind speed on specific speed (λ)*

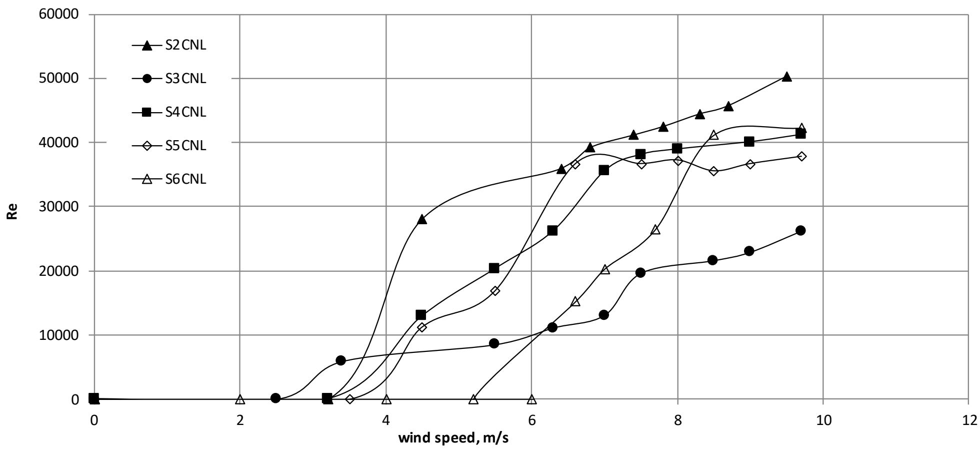

Fig. 20. *The influence of wind speed on the Re number*

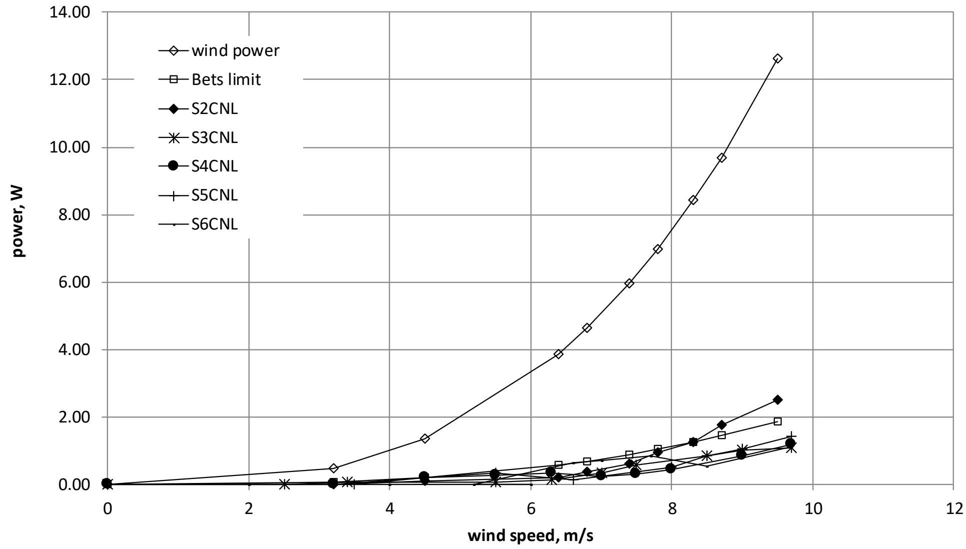

Fig. 21. *The influence of wind speed on power*

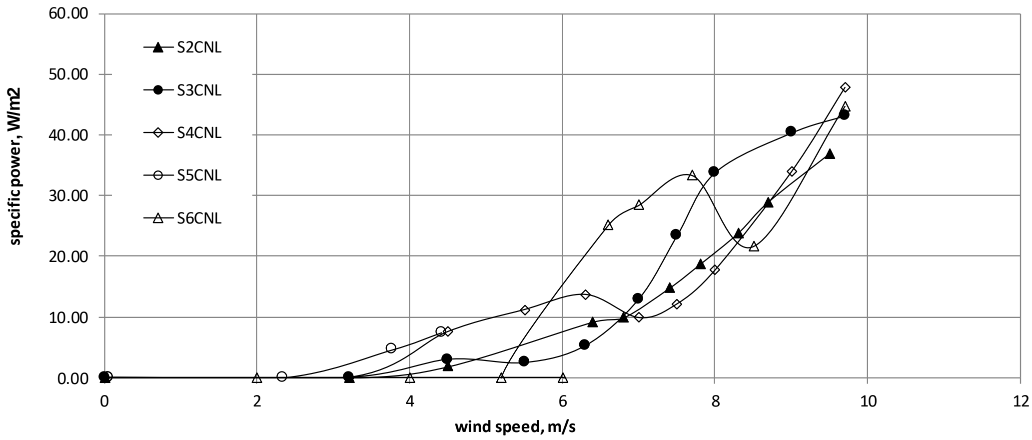

Fig. 22. *The influence of wind speed on specific power*

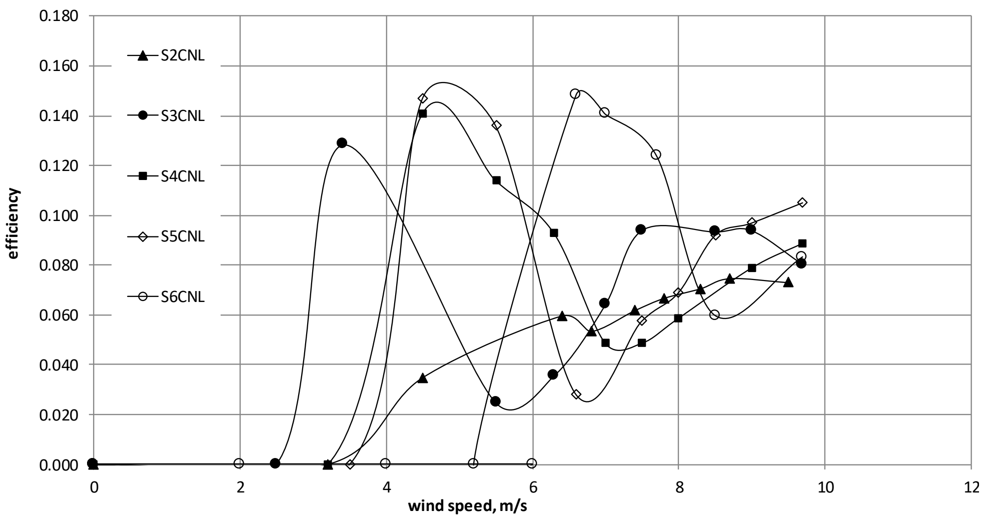

Fig. 23. *The influence of wind speed on the efficiency of converting wind energy into mechanical work*

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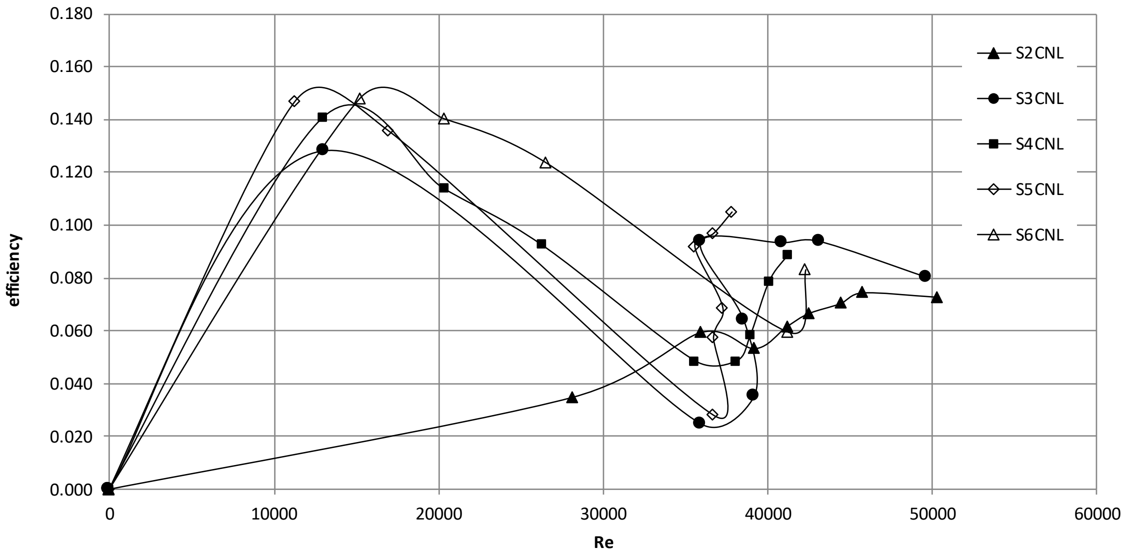

Fig. 24. *Variation of conversion efficiency with the Re number*

The Betz limit (14.81%) also varies with the same allure, which represents the maximum limit for the conversion of wind energy into other forms of energy. All the shaft powers for the researched experimental models are above this value.

In Fig. 20 it is observed that the allure of the specific power variation curves at the axis have a local maximum that is positioned depending on the number of blades of the experimental model.

The efficiency of the conversion of wind energy into mechanical work is shown in Fig. 21. It is observed that the efficiency depends on the number of cups of the model. For all experimental models the efficiency has an area where a local maximum is present, followed by a minimum and then an increase in efficiency up to the test speeds used given below the value of the local maximum. The peripheral speed of the experimental model u cannot be greater than the wind speed v unless forces other than D (drag force) appear. For all experimental models subjected to experiments in the wind tunnel we have a maximum influence of the Re number on the conversion efficiency (Fig. 22). Thus, S2CNL has 6% at Re about 35000.

The variation curves have the same allure of variation and the Re number increases approximately linearly to lambda 0.7 to 0.8 (Fig. 23). The linear areas depend on the number of cups and there is an increase in the Re number with the number of cups. After a value the Re number increases with decreasing peripheral speed of EM (lambda decreases).

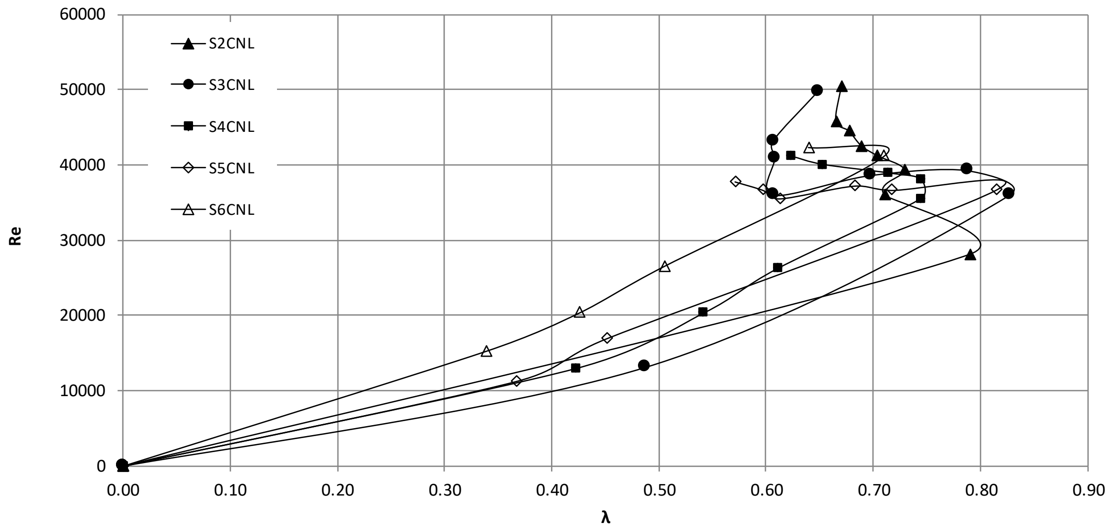

Fig. 25. *The influence of Lambda specific speed on the Re number*

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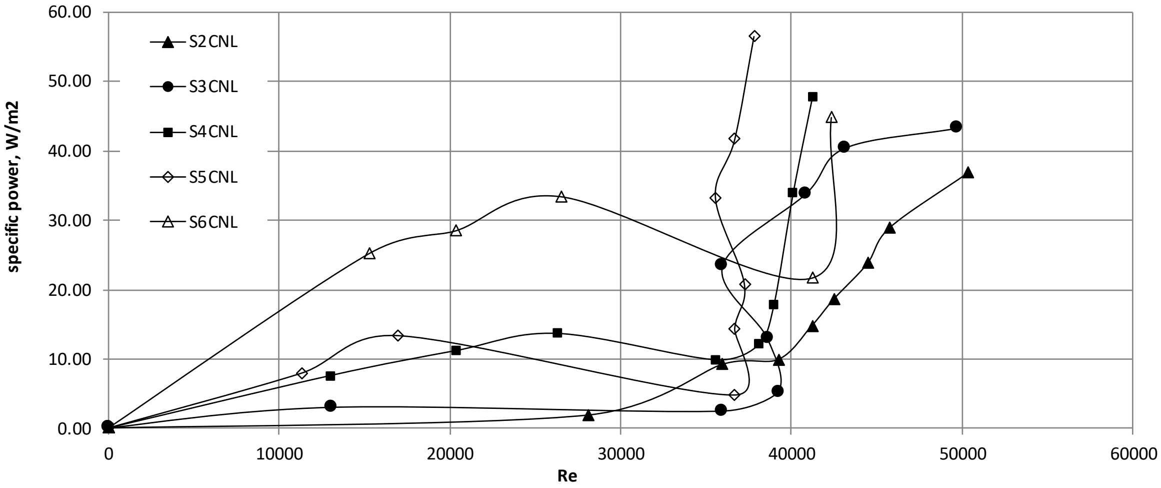

Fig. 26. *Influence of the Re number (flow quality) on axis specific power*

Axis-specific power variation curves have a local maximum at a value of the Re number that depends on the number of cups of EM. Thus, the EM with six S6CNL blades reaches 34 W/m^2 at 25000 Re and the one with 5 cups (S5CNL) 14W / m2 at Re 15000. This EM has after Re 35000 an increase of the specific power up to over 55 W/m^2. The experimental models with two cups (S2CNL) and three cups (S3CNL) reach 25 W/m^2 at Re 50000 and 45 W/m^2 at Re 50000, respectively.

4. Conclusions

Wind energy is a form of energy that can be partially converted into mechanical work and then into electrical energy through the Betz limit. Energy conversion is supported by a mathematical model of conversion and by various structures of the wind system.

The paper focused on the Savonius VAWT model for which the experimental VAWT models were developed. The number of semi-cylindrical cups of some Savonius experimental models with 2, 3, 4, 5 and 6 semi-cylindrical cups have been modified (SC2CNL, SC3CNL, SC4CNL, SC5CNL and SC6CNL).

The results show that under the wind test conditions between 0…9.7 m/s, we have a major influence of the number of semi-cylindrical cups on the rotation speed of the experimental models.

All experimental models have a stop threshold which also depends on the number of semi-cylindrical cups of the experimental model.

It is found that the 3-cup EM co (S3CNL) has the best sensitivity to low wind speeds (Fig. 16).

The lowest sensitivity and the highest stopping threshold are at EM with 5 and 6 semi-cylindrical cups (S5CNL and S6CNL).

The model with two semi-cylindrical cups (S2CNL) reaches the maximum speed as over 60000. The high values of the Re number also contribute to the fineness of the surface of the material used to make semi-cylindrical cups (0.4mm thick laminated aluminum sheet). The most uniform increase of the Re number 0 has EM with 2 cups (S2CNL) which after a rapid increase at the Re number 30000 at about 5.5 m/s has an approximately linear increase up to over 60,000.

For S4CNL, S5CNL and S6CNL (Fig. 20) the values of the local maximum specific power increase and the highest value corresponds to the model with 6 cups, being almost 35 W/m^2.

Regarding the efficiency of conversion (Fig. 21), the S2CNL has the lowest efficiency of 6%; S3CNL reaches 13% and S4SNL at over 14%. The experimental models with 5 and 6 cups (S% CNL and S6CNL) is close to the maximum efficiency limit for this VAWT model, which has as driving force D (drag force). The efficiency of the conversion depends on the wind speed with a maximum curve for each experimental model (Fig. 21). A similar dependence is on the Re number. The efficiency of the conversion depends on the wind speed with a maximum curve for each experimental model. A similar dependence is on the Re number (Fig. 22).

With the increase of the number of semi-cylindrical cups to five and six respectively, the efficiency of the conversion of wind energy into mechanical work reaches almost the Betz line (14.81%) specific for this type of VAWT, at 4.5 m/s and 6.5 m/s, respectively.

References

[1]. Hau Erich, *Wind Turbines, Fundamentals, Technologies, Applications, Economics*, s.l.: Springler, 2006.

[2]. Manwell J. F., McGowan J. G., Rogers A. L., *Wind Energy Explained. Theory, Design and Application*, s.l. John Wiley & Sons Ltd., p. 590, 2002.

[3]. The European Wind energy association, *Wind in power*, 2010 European statistics, 2011.

[4]. Piggot Hugh, *Small Wind Turbine Design Notes*, 1998.

[5]. Menet J. L., Bourabaa N., *Increase in a savonius rotor efficiency*.

[6]. Archer Cristina L., Jacobson Mark Z., *Evaluation of global wind power*, Journal of Geophysical Research, vol. 11, D12110, 2005.

[7]. Cazacu Nelu, *Load Behavior of a Vertical Axle Wind Turbine Model with Four Blades Periodically Couple Aerodynamically*, The Annals of "Dunarea de Jos" University of Galati, Fascicle IX, Metallurgy and Materials Science, Galati University Press, vol. 3, p. 5-11, ISSN 2668-4748; e-ISSN 2668 4756, 2018.

[8]. Cazacu Nelu, *Improving the Powerful Behavior of an ExperimentaL model of Savonius Turbine (S-rotor) with Couple Aerodynamic Additional Blades*, The Annals of "Dunarea de Jos" University of Galati, Fascicle IX, Metallurgy and Materials Science, Galati University Press, vol. 2, p. 49-53, ISSN 1453-083X, 2018.

[9]. Cazacu Nelu, *The Influence of Number of Blades and the Number of Levels on Behaviorof the "S-rotor" Experimental Model*, The Annals of "Dunarea de Jos" University of Galati, Fascicle IX, Metallurgy and Materials Science, Galati University Press, vol. 4, p. 58-63, ISSN 1453-083X, 2017.

[10]. Cazacu Nelu, *The Behavior of an Experimental Model of Wind Turbine with Vertical Axle with Overlapped Cups at Low Wind Speeds*, The Annals of "Dunarea de Jos" University of Galati, Fascicle IX, Metallurgy and Materials Science, Galati University Press, vol. 4, p. 51-57, ISSN 1453-083X, 2017.

[11]. Cazacu Nelu, Lucaci Bogdan Cătălin, *Functional Model of Savoniuus Type Verrtical Axis Wind Turbine with Periodoc Coupling of Adjacent Vertical Blades*, The Annals of "Dunarea de Jos" University of Galati, Fascicle IX, Metallurgy and Materials Science, vol. 4, p. 69-76, 2014.