THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 4 – 2014, ISSN 1453 – 083X

FUNCTIONAL MODEL OF SAVONIUS TYPE VERTICAL AXIS WIND TURBINE WITH PERIODIC COUPLING OF ADJACENT VERTICAL BLADES

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ABSTRACT

The field of HAWT (Horizontal Axis Wind Turbines) regarding the use of wind energy (WE) as a renewable energy source (RES) is well researched and the results are covering both the power range and efficiency. Deficiencies observed during high wind speeds affect the investment costs. Savonius is a VAWT (Vertical Axis Wind Turbine) used for low wind speed, with low costs and low efficiency. The study proposes a conceptual model of Savonius type of VAWT (SWT) meant to increase the efficiency by reducing the resistance of the returning blade. SWT conceptual models were studied and analyzed and then a MC was elaborated and a MF and MM have been developed. An ME was made based on the MC and MF, which was used in wind tunnel experiments. The starting torque, the power factor, the efficiency, the speed and the output voltage of the generator were investigated. The results confirm the viability of the model and its resources to increase efficiency.

KEYWORDS: wind energy, VAWT, Savonius, coupled blades

1. Introduction

A classification of WT based on the rotation axis position leads to HAWT, which are the most widespread, and VAWT, less prevalent and less effective.

The literature recognizes that the main advantage of vertical axis wind turbines, namely the lack of wind direction dependence, leads to some simplifications in the handling of the problem.

A graphical representation of the power coefficient Cp, presented in many studies, leads to fields of application of various types of wind turbines depending on wind speed vi or speed coefficient λe. The diagram highlights the existence of the relative speed as an important element in the design and operation of a wind turbine:

Notations
v_v - *wind speed input (to infinity) m/s*
u - peripheral speed at the top the blade, m/s
R - the radius of the disc base, m
c - overlap, m
d - width of blade, m
h - height of blade, m
ω - angular speed, radians/s
λ - coefficient of speed (speed index)
Cp - power index
n - number of blades on the floor
m - number of floors

Abbreviations
WE – wind energy
WT – wind turbine
VAWT – vertical axes wind turbine
HAWT– horizontal axes wind turbine
SWT – Savonius Wind Turbine
SBWT – Savonius-Benesh Wind Turbine
SWT-API – SWT with Alternating pocket/interval
RES – Renewable Energy Sources
d.c. – direct current
Re – Reynolds number

$$\lambda_e = \frac{v}{v_i} \quad (1)$$

The tangential speed at the blade tip is dependent on angular velocity and the radius of rotation:

$$v = \omega R \quad (2)$$

The Savonius type wind turbine (SWT) has a low power coefficient (max. 18%) and λe max 1.5, which shows low rotation speed and also small tangential speed at the blade tip (Menet, and *et al.*).

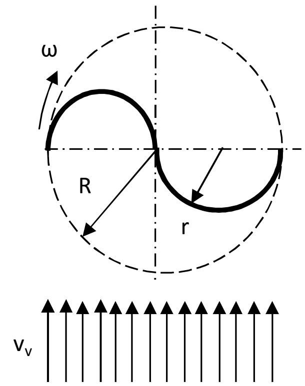

Fig. 1. *Section through Savonius Wind Turbine (SWT)*

SWT theory explains this by the braking effect of the blade during the return. One method to reduce the resistive return effect is to move the air stream after the mechanical work is done from the pressure side to the return side.

FEM simulations (Menet, and *et al.*) highlight the causes of SWT low efficiency, i.e. gas-dynamic braking determined by adverse changes in the pressure.

The operation of this type of wind turbine is characterized by changing the rotation angle of the torque generated by a pair of pales, in the original and simplest situation.

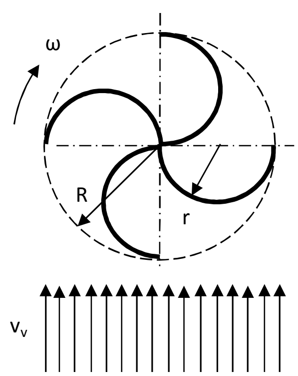

Fig. 2. *SWT with four semicilindrical blades*

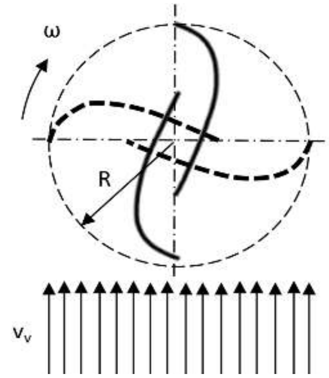

Fig. 3. *SWT with Benesh airfoil: one real pair of blades and fictive second pair of blades*

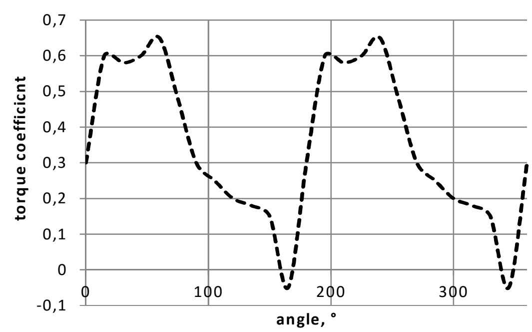

Fig. 4. *Variation of couple to axe for SWT (Menet, et al.)*

2. Experimental

The objectives in this paper are:
• increasing the wind speed range;
• increasing the efficiency;
• reducing the resistance of the returning blade;
• changing the blade profile.

The reference literature offers a great number of conceptual (theoretical) models and experimental models. They are based on a SWT or VAWT, so called "S wind turbine" because of the specific blade section profile.

The CM proposed in this paper is a SWT model modified to reduce the drag resistance of reverse blade without using control screens that reduce the main advantage of SWT i.e. the independence from wind speed.

The development of a conceptual model containing elements of novelty is possible after a complete and critical analysis of data from the relevant literature and beyond. The interest in the construction of cheap wind turbines for families is high where an RES exists.

The premises for SWT use are as follows:
• VAWT type;

- independence from wind speed;
- operation at low wind speeds;
- great solidity coefficient;
- great surface;
- problems during storms and wind blasts.

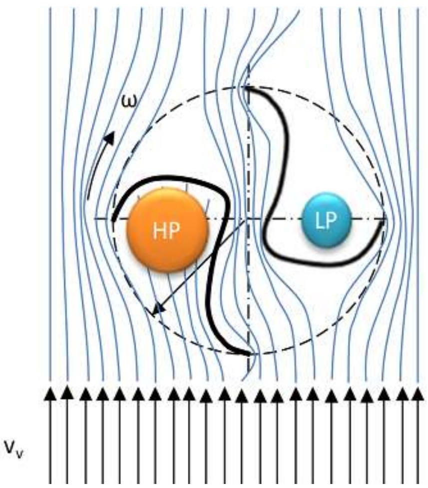

Fig. 5. *Alternating "pocket/interval" (API) for SWT with coupling blades (superior level)*

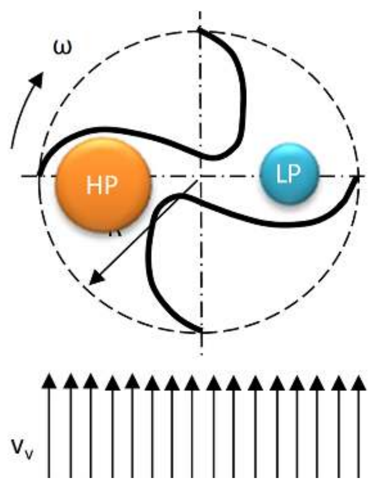

Fig. 6. *Alternating "pocket/interval" (API) for SWT with coupling blades (inferior level)*

The following factors of influence shall be noted:

SWT operates based on the forces of wind (D-Draft force).

The driving torque is given by the force Draft at a given time and the force arm.

Reducing the blade surface and increasing the radius is a solution for increasing the axis torque.

The torque and blade angle shall be rendered uniform with wind speed by two methods.

An advantage is increasing the number of blades, while a disadvantage will be a uniform torque, increasing inertia, mass will also be increased.

Blades staggering by reducing the height and creating stages (Helix).

Measurements and simulations show that a disturbed zone is produced in the SWT area, with local increases/decreases of the pressure, and hence the formation of local currents (vortices), reducing the efficiency of the system. As a Drag-type system, SWT efficiency increases with reducing the pressure difference.

In principle, the conceptual model is based on creating a gas-dynamic channel between two pairs of blades with approximate Benesh (Benesh, 1988) structure and layout, which provides a fast equalization of pressures.

When 2, 3 or 4 pairs of blades may be used with changing the distances, this will involve the smooth operation of the gas-dynamic turbine.

In principle, the following effects occur:

- reduction of the variability of a torque around a rotation axis due to a lower differential pressure (pressure/depressure).

- uniformization of torque to axis as a result of superposition of several blades.

- increase in the starting torque due to the constant wind speed.

- torque uniformization.

3. Functional Model

The CM proposed that SWT starts from the use of pairs of blade in continuous or overlaying a gap case. The different behavior of the pair of blades in a lower wind speed gives the difference of force, coupled forces and finally a rotation.

Increasing the torque on the back masking blade is useful but the advantage of independence from wind direction will be lost.

If SWT has two blades the torque varies with the rotation angle measured from the direction of the wind (Menet reference).

Wind is a variable load and efficiency is low.

The CM proposed uses physical coupling and gas dynamics of the 4 vertical blades of the SWT. The coupling is made between adjacent blades and thus creates a succession "pocket/range" both diametrically high and using the opportunity to increase the pressure behind the blade through the front airflow created by the constructive interval.

The MM (mathematical model) of wind energy, widely available in literature, takes into consideration the kinetic energy of a moving air stream, using Betz's calculations to obtain an energy conversion before and after the wind rotor (v) to have a certain value. When the wind speed after rotor v = 0, the wind cannot pass through the rotor blades; when the wind speed brake rotor is not 0, energy transformation will take place.

The optimum value brake wind is obtained to value ratio: $\frac{v_3}{v_1} = \frac{1}{3}$.

We obtain values corresponding to this optimum value of power coefficient (aerodynamic efficiency).

$$c_p = \frac{16}{27} = 59.3\%$$

The plan has the speed wind rotor $v_2 = \frac{2}{3}\ v_1$.

Particularly, in the case of vertical axis wind turbines, Betz’s limit has a value up to 14.81%.

The conversion of wind energy can be made according to the following schemes:

Wind Energy>Work>Electric Energy

VAWTs are generally of the “Drag-force” type, i.e. push or wind drag. This means that, if a body is in a system with the central axis of rotation under the influence of the wind, a pushing force is created, which, in turn, generates a torque towards axis, pushing force is for an object fixed on the surface placed in the path of an air flow:

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

C_D is defined as an important parameter when it comes to wind resistance. The power lost by wind, namely the power gained by the body, is as follows:

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

In case of “Drag-force” wind turbines, the relative speed is as follows:

$$v_r = v_0 - u \qquad (8)$$

Where v_v - wind speed, m/s; u – tip blade speed, m/s:

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

The power extracted at SWT axis is given by the formula:

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

The axis torque is as follows:

$$P = C_m \rho_a R^2 H v_i^2 \qquad (4)$$

Air density affects the power and this influence is determined by the relation:

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

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

$$\eta = \frac{P}{P_v} = \frac{\frac{1}{2}\rho (v_v - u)^2 C_D u A}{\frac{1}{2}\rho A v_v^3} \qquad (10)$$

$$\eta = \frac{(v_v - u)^2 C_D u}{v_v^3} \qquad (11)$$

4. Experimental condition

An experimental wind tunnel with the following characteristics was used for experiments:

• anchoring the experimental model (ME) of VAWT;

• allowing easy exchange of EMs;

• allowing measurement of sensor location (force, speed, pressure).

The experiment performed a number of experimental models that changed the limits of a number of factors.

The purpose of the experiments is to verify the assumptions mentioned and then to find mathematical expressions that give theoretical explanations.

The construction is made of two steel plates, the lower and upper columns and 6 of the work 2 (M8) and 4 abutment and stiffening (M6):

• motherboard dimensions: 282 x 235 mm;

• height: 498 mm.

VAWT experimental models are supported on two rails 300 x 40 x 8 mm. When operating, these columns can be fixed with nuts and washers. The center bearings are fixed and centering devices ME discs.

A simple and efficient anemometer was made from a table tennis ball and a pendulum application.

The experimental metal frame presented in Figure 7has the following functions:

- to allow the anchorage of the EM of VAWT;
- to allow easy change of EMs;
- to allow the placement of measurement sensors (force, speed, pressure).

Experimentally, a number of experimental models shall be made, where the number of factors shall be changed in the established limits.

The purpose of the experiments is to verify the mentioned assumptions and then to find mathematical expressions.

It is a four blade model SWT modified by alternate coupling of blades on pocket/range section and ½ height alternating pocket/interval (API). A number of EMs have been built on the CM to verify functionality and performance.

Fig. 7. *Alternating "pocket/interval" blade over diametral and axial for EM of SWT*

The EM characteristics are:
• type with changes SWT API;
• number of blades: 4;
• number of horizontal pockets: 2;
• number of intervals horizontally: 2;
• number of vertical alternation: 1;
• maximum diameter: 0,150 m;
• blade height: 0.390 m;
• airfoil: approx. Benesh;
• airfoil material: PE cellulated;
• blade material thickness: 0.003 m.

5. Results and discussion

The wind speed influence over the open loop turbine rotations is the simplest experiment. The wind turbine is attached on a support frame containing centered axial bearings which allow the setting of EMs with heights of 50...495 mm and maximum diameters of 250 mm.

Table 1. *Values of wind speed versus wind energy*

exp. no.	wind speed	wind energy	wind power	wind specific power	Bets limit 14.81%
u.m.	m/s	J	W	W/m^2	W
1	3.62	98.13	1.64	27.96	0.24
2	3.98	130.42	2.17	37.16	0.32
3	3.35	77.77	1.30	22.16	0.19
4	2.88	49.42	0.82	14.08	0.12
5	2.37	27.54	0.46	7.85	0.07
6	2.14	20.27	0.34	5.78	0.05
7	2.12	19.71	0.33	5.62	0.05
8	1.83	12.68	0.21	3.61	0.03
9	1.81	12.27	0.20	3.49	0.03
10	1.62	8.79	0.15	2.51	0.02
11	0	0	0	0	0

In the wind speed range of 0...4.5 m/s and when there is no load, the variation of the axis speed and the wind speed are shown in Fig. 4.

In Fig. 5 are shown the variations of Re which has a constantly growing number of wind speed (Fig. 11) and specific speed (Fig. 14) in the range of wind speeds used in the experiments. The Re number is a constantly growing number of wind speeds (Fig. 11) and specific speeds (Fig. 14) in the range of wind speeds used in the experiments.

The efficiency of the SWT EM with "pocket/Interval" coupled blades is shown in Figs. 8 and 9. A maximum efficiency around 0.12 was obtained for wind speed around 2 m/s and λ_e between 2.23 and 0.39.

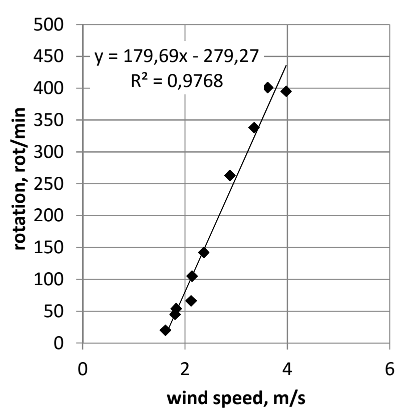

Fig. 8. *EM speed variation with wind speed*

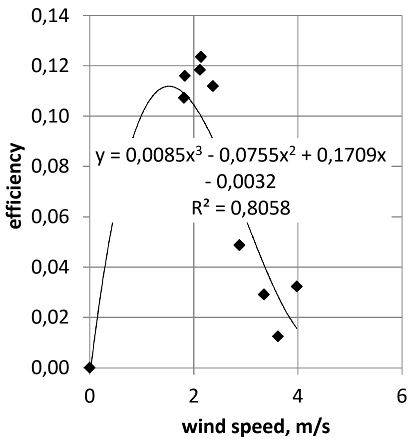

Fig. 9. *Wind speed influence over efficiency*

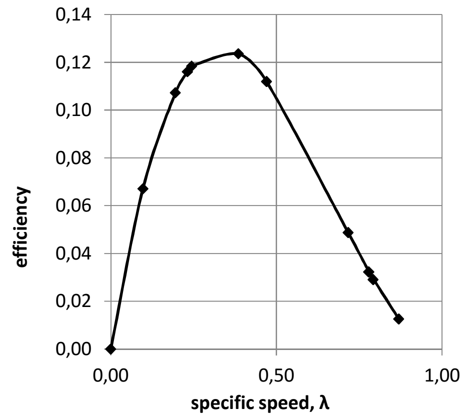

Fig. 10. *Specific wind speed influence over efficiency for EM*

Table 2. *Values regarding speeds of rotating components and the obtained power*

u.m.	rot/min	rot/s	Hz	rad/s	m/s	-	-	W/m^2	W	-
1	401	6.68	6.68	41.97	3.15	0.87	64242	0.35	0.021	0.01
2	395	6.58	6.58	41.34	3.10	0.78	63281	1.20	0.070	0.03
3	338	5.63	5.63	35.38	2.65	0.79	54149	0.64	0.038	0.03
4	263	4.38	4.38	27.53	2.06	0.72	42134	0.69	0.040	0.05
5	142	2.37	2.37	14.86	1.11	0.47	22749	0.88	0.051	0.11
6	105	1.75	1.75	10.99	0.82	0.39	16821	0.71	0.042	0.12
7	66	1.10	1.10	6.91	0.52	0.24	10573	0.66	0.039	0.12
8	54	0.90	0.90	5.65	0.42	0.23	8651	0.42	0.025	0.12
9	45	0.75	0.75	4.71	0.35	0.20	7209	0.37	0.022	0.11
10	20	0.33	0.33	2,09	0.16	0.10	3204	0.17	0.010	0.07
11	0	0	0	0	0	0	0	0	0	0

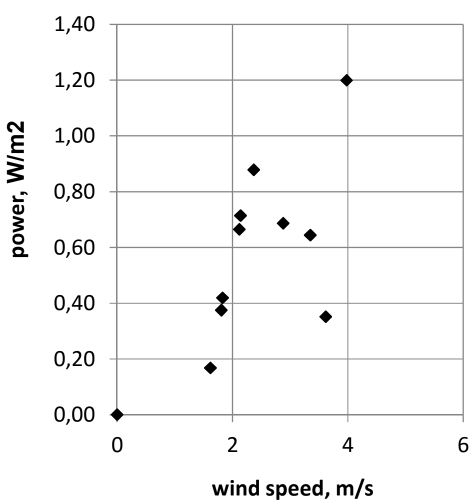

Fig. 11. *Power dispersions with wind speed for EM*

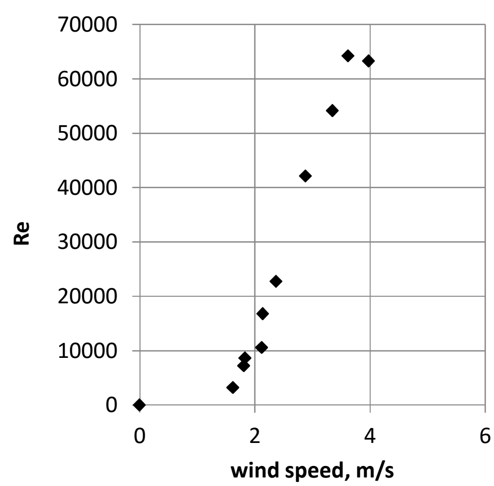

Fig. 12. *Re number variation with wind speed*

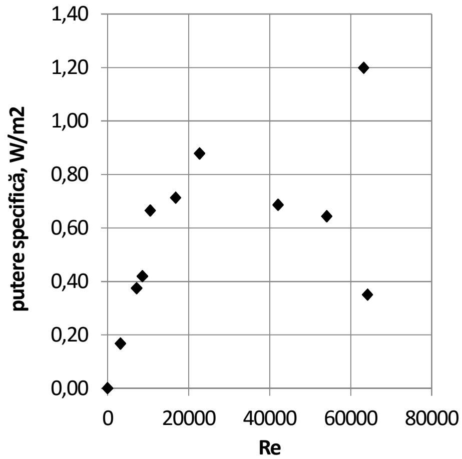

Fig. 13. *Specific power with Re number for EM*

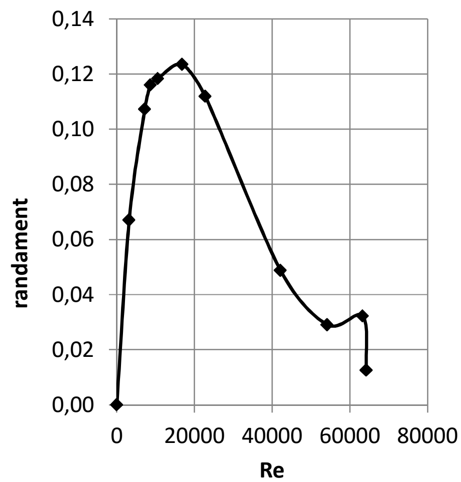

Fig. 14. *Efficiency with Re number for EM*

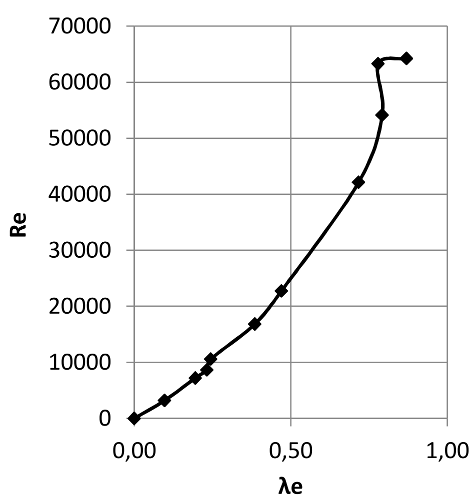

Fig. 15. *Re number variation with λe*

6. Conclusions

In the tests conducted in the wind tunnel, it is observed that the model developed has acceptable behavior.

The concept initially described is checked in the experimental model to have a rotating uniformity and more functionality is explained by the flow channels of "pocket/interval".

The EM was tested in no load conditions. An efficiency of 12 % was achieved for a range of wind speeds between 1.83 ... 2.14 m/s and λe = 0.23 ... 0.39.

Reynolds number continues to increase with wind speed aprox. 65000 (Fig. 12) and depending λe (λe = 1) drive situation shown in Fig. 15.

The maximum efficiency model for Re is obtained at about 20000 (Fig. 14) and a relative speed of 0.35.

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