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THE BEHAVIOR OF AN EXPERIMENTAL MODEL OF WIND TURBINE WITH VERTICAL AXLE WITH OVERLAPPED CUPS AT LOW WIND SPEEDS

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ABSTRACT

This work is based on an experimental model of vertical axis wind turbine (VAWT), which used a pair of hemispherical blades (cups) with variable overlap. Maintaining the rotation speed to a constant value and in order to meet an important criterion for a current generator fitted to the shaft via a speed multiplier is achieved with a centrifugal mechanism. The experiments conducted in laboratory conditions using experimental model wind tunnel at speeds below 4.5 m/s confirm the validity of the concept.

KEYWORDS: vertical axis wind turbine (VAWT), airfoil, hemispheric cup, overlap, gap

1. Introduction

Vertical axis wind turbines (VAWT) have as main characteristic simplicity constructive and independent of wind direction. "Savonius rotor", "Darrieus rotor" and "H-rotor" are considered the most representative classes VAWT [1].

Savonius wind turbine (SWT), with Savonius rotor, also called S-type rotor (see Fig. 1(b), Figure 2) is a wind vertical axis that uses "drag force", which represents tangential limit their speed of rotation that values close to the wind speed ($\lambda \approx 1$).

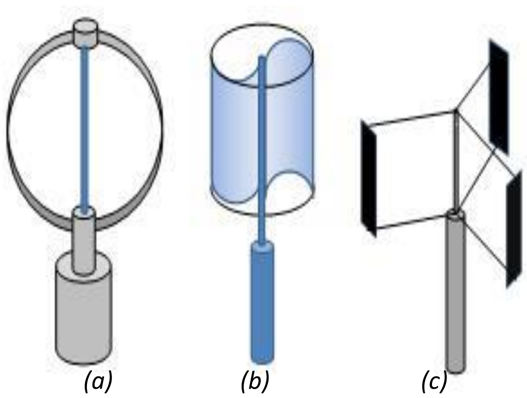

***Fig. 1.** VAWT main models: (a) DWT - Darrieus wind turbine; (b) SWT - Savonius wind turbine; (c) HWT - "H" type wind turbines [1]*

SWT has a limited field of use determined by small output, with a maximum of approximately 18% (Betz limit) and a rotation speed low (λ = 0,5 ... 1,5). Use as aero water pumping systems is the best [2, 3].

Darrieus wind turbine (DWT, Figure 1 (a)) is a high-speed VAWT that uses "lift force", and has 2 or 3 blades. DWT is the main advantage of higher tangential speed, which offers advantages for use in power generation.

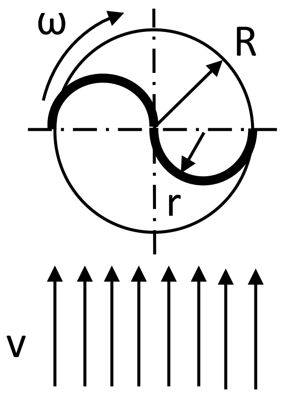

***Fig. 2.** Savonius wind turbine*

"H" type wind turbine (HWT) comes from DWT and represents the middle portion, which led to specific construction building structures with simplifications in achieving the tower and anchor and especially balancing axial forces.

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

$$E = \frac{1}{2} m v^2 \tag{1}$$

where: E – wind kinetic energy, [J];
m – air mass, [kg];
v - is the wind speed, [m/s].

The volume flow over the swept area is:

$$\dot{V} = A \cdot v \tag{2}$$

where: $\dot{V}$ – air volume flow, [m^3];
A – rotor swept area, [m^2].

And the mass flow results in:

$$\dot{m} = \rho \cdot A \cdot v \tag{3}$$

where: $\dot{m}$ - air mass flow, [kg];
ρ - air density, [kg/m^3].

Hence, the power (energy per second) results:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \tag{4}$$

where: P – wind power, [W].

According to Betz's law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient. The Savonius wind turbines (SWT) operate on the drag force and have much lower performance, approximately 15% (14.81%, with a Betz limit of maximum 4/27). Under the influence of the wind speed, the blades move at the velocity *u* under force *D* (Figure 3).

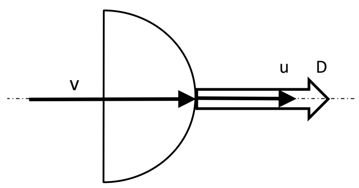

Fig. 3. *Drag force on each blade and wind [4]*

The drag force is [4]:

$$D = C_D \frac{1}{2} \rho (v-u)^2 A \tag{5}$$

where: D – drag force, [N];
C_D - drag coefficient;
u - is the flow velocity relative to the object (rotor blade velocity).

The power obtained to each blade is:

$$P = D_u = C_D \frac{1}{2} \rho v^3 (1 - \frac{u}{v})^2 \frac{u}{v} A \tag{6}$$

A dimensionless speed ratio is:

$$\lambda = \frac{u}{v} \tag{7}$$

And power at turbine axle is [4]:

$$P = C_D \frac{1}{2} \rho v^3 (1-\lambda)^2 \lambda A \tag{8}$$

2. Experimental conditions

The schematic view of experimental model (EM) proposed with hemispheric cups is shown in Figure 4.

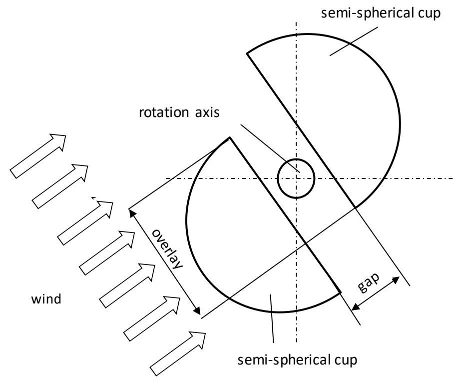

Fig. 4. *Schematic of VAWT Experimental Model with hemispheric cups*

Figure 5 shows the experimental model for VAWT with hemispheric cups tested.

Fig. 5. *Experimental Model for VAWT with hemispheric cups*

The specifications of the scale model are shown in Table 1 and Table 2 presents the experimental conditions.

Table 1. *Experimental model characteristics*

no.	symbol	characteristics	value	m.u.	observation
1	r	sphere radius (cup)	0,055	m	cup shape
2	R	turbine radius	0,093	m	
3	n	blade number	2	-	
4	k	level number	1	-	
5	gmax	cup wall thickness	0,002	m	
6	gm	depth blade material	0,002	m	
7	PEc	blade material ME	-	-	PS
8	lp	blade long	0,173	m	
9	Sd	total blade surface	0,019	m2	
10	0	cup surface	0,009	m2	
11	S	swept area:	-	m2	
12	Smin	min	0,009	m2	
13	Smax	max	0,017	m2	plan diametral perpendicular pe vant
14	τ	rotor solidity:	0	0	
15	τmin	min	0,556	-	
16	τmax	max	1	-	
17	a	gap	0	m	variable
18	s	overlap	0,3	-	v ariable: 35...55%

Table 2. *Experimental conditions*

no.	symbol	characteristics	value	m.u.	observation
1	ta	air temperature	22	°C	measured
2	z	site altitude	40	m	Galati
3	Ta	absolute air temperature	295,16	K	0
4	0	air humidity	0	0	(Nelson, 2009), site
5	ρas	standard air density	1,225	kg/m3	15°C, sea level
6	ρa	real air density	1,19064558	kg/m3	with corrections (2) (Nelson, 2009)
7	Pr	atmospheric pressure	780	mmHg	measured
8	va	kinematic viscosity of air	0,00001568	m2/s	
9	ηa	dynamic viscosity of air	0,00001983	Ns/m2	
10	C_D	power coefficient of drag devices	1	-	(Nelson, 2009)
11	τ	time	60	s	measured
12	VP	vapour pressure	0	mmHg	

For the test experiments, a low-speed tunnel was used (V = 0...5 m/s) and a measurement section de 0,5 m x 0,5m. (S = 0,025 m^2). The swept surface was between 0.005 m^2 to 0.011 m^2 and was dependent on the overlay degree of the hemispherical cups (35% to. 55%).

3. Results and discussion

Performance results are presented in this section. The experimental data are presented in Table 3, Table 4, Table 5 and Table 6 and describe typical behaviour of "D-force" wind turbine [1, 5].

Table 3. *Obtained data for EM in wind tunnel experiments for 55% blade overlay*

exp.no.	revolutions		frequency	unghiular speed	periferic speed	specific speed	Reynolds number	specific power	power	conversion efficiensy
symbol	n		f	ω	vt	λ	Re	P/A	Pa	η
u.m.	rpm	rot/s	Hz	rad/s	m/s	-	-	W/m^2	W	-
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
9	180	3,00	3,00	18,84	1,75	0,42	65613	5,05	0,03	0,12

Table 4. *Obtained data for EM in wind tunnel experiments for 45% blade overlay*

exp.no.	revolutions		frequency	unghiular speed	periferic speed	specific speed	Reynolds number	specific power	power	conversion efficiensy
symbol	n		f	ω	vt	λ	Re	P/A	Pa	η
u.m.	rpm	rot/s	Hz	rad/s	m/s	-	-	W/m2	W	-
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	45	0,75	0,75	4,71	0,44	0,14	15149	1,72	0,01	0,08
5	87	1,45	1,45	9,11	0,85	0,25	29288	2,84	0,02	0,12
6	109	1,82	1,82	11,41	1,06	0,29	36694	3,44	0,02	0,12
7	157	2,62	2,62	16,43	1,53	0,40	52853	4,03	0,03	0,12
8	187	3,12	3,12	19,57	1,82	0,45	62952	4,33	0,03	0,11
9	189	3,15	3,15	19,78	1,84	0,44	63625	4,92	0,03	0,12

Table 5. *Obtained data for EM in wind tunnel experiments for 40% blade overlay*

exp.no.	revolutions		frequency	unghiular speed	periferic speed	specific speed	Reynolds number	specific power	power	conversion efficiensy
symbol	n		f	ω	vt	λ	Re	P/A	Pa	η
u.m.	rpm	rot/s	Hz	rad/s	m/s	-	-	W/m2	W	-
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
5	48	0,80	0,80	5,02	0,47	0,14	16159	1,79	0,02	0,09
6	129	2,15	2,15	13,50	1,26	0,37	43427	2,99	0,03	0,12
7	147	2,45	2,45	15,39	1,43	0,40	49486	3,39	0,03	0,12
8	171	2,85	2,85	17,90	1,66	0,44	57566	3,88	0,04	0,12
9	189	3,15	3,15	19,78	1,84	0,46	63625	4,30	0,04	0,11
0	192	3,20	3,20	20,10	1,87	0,45	64635	4,87	0,05	0,11

Table 6. *Obtained data for EM in wind tunnel experiments for 35% blade overlay*

exp.no.	revolutions		frequency	unghiular speed	periferic speed	specific speed	Reynolds number	specific power	power	conversion efficiensy
symbol	n		f	ω	vt	λ	Re	P/A	Pa	η
u.m.	rpm	rot/s	Hz	rad/s	m/s	-	-	W/m2	W	-
1	0	0	0	0	0	0	0	0	0	0
2	39	0,65	0,65	4,08	0,38	0,14	13129	0,99	0,01	0,09
3	86	1,43	1,43	9,00	0,84	0,27	28951	2,07	0,02	0,12
5	141	2,35	2,35	14,76	1,37	0,42	47466	2,38	0,03	0,12
6	135	2,25	2,25	14,13	1,31	0,38	45447	2,97	0,03	0,12
7	155	2,58	2,58	16,22	1,51	0,42	52179	3,32	0,04	0,12
8	180	3,00	3,00	18,84	1,75	0,46	60595	3,76	0,04	0,11
9	189	3,15	3,15	19,78	1,84	0,46	63625	4,30	0,05	0,11
0	207	3,45	3,45	21,67	2,01	0,49	69685	4,61	0,05	0,11

The data are first shown in terms of rotation speed rate (Figure 6), specific speed (Figure 7), Reynolds Number (Figure 8), specific power (Figure 9), power to the turbine shaft (Figure 10) and efficiency (Figure 11) for a range of wind speed (0 - 5 m/s) and different overlay (35% - 55%).

Figure 6 presents the speed variation in rpm with wind speed for different overlay. The maximum rpm is for 35% overlay and 4,2 m/s. Specific speed λ, was 0.5 for wind speed 4,2m/s and overlay 0.35.

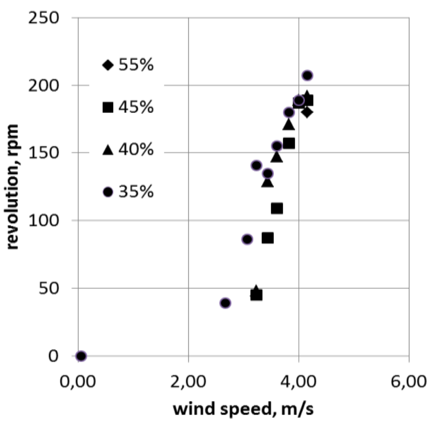

Fig. 6. *Rotation speed variations of EM with the wind speed for different overlay*

Figure 7 shows the specific speed variations of experimental model depending on wind speed at different overlay. Except for the experiments when *u* = 0, with no starting torque, λ approaches 0.5 for wind speeds approaching the maximum limit used for experiments.

The Reynolds Number (R_e) is the decisive factor in the air-flow in determining whether the inertial effect or the viscous effect wins. A low Reynolds Number gives laminar flow while a high Reynolds Number gives turbulent flow. Since the change in the Reynolds numbers influences the rotor design in many respects, in Figure 8 are presented the calculated Reynolds number as a function of wind speed under different overlay.

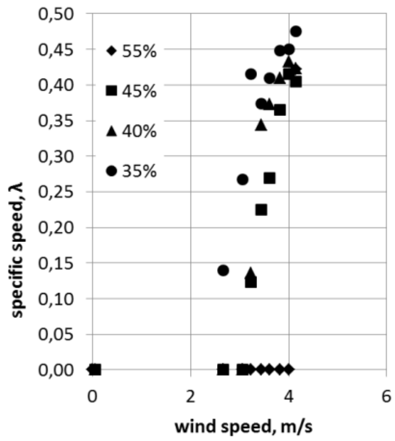

Fig. 7. *Specific speed variations of EM with the wind speed for different overlay*

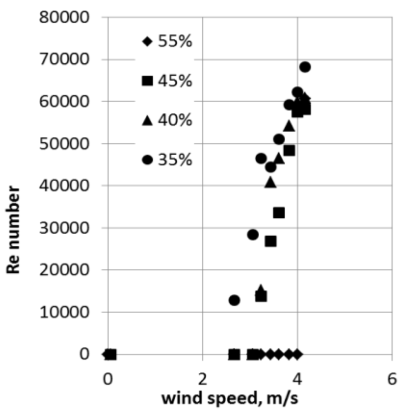

Fig. 8. *Re number variation for EM with the wind speed for different overlay*

Re number has a continuous increase for all experiments up to 70000 and the overlapping influence is small (Figure 8).

Figure 9 shows the specific power variations of experimental model depending on wind speed at different overlay.

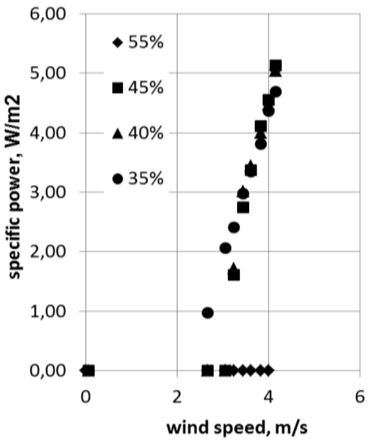

Fig. 9. *Specific Power of EM depending on wind speed and for different overlay*

Except in situations where EM had zero rotations speed, before having the starting torque, the specific power developed at the axle increases with the wind speed for all the experiments performed (Figure 9).

In Figure 10 is presented the power to the turbine shaft corresponding to experimental model depending on the wind speed at different overlay.

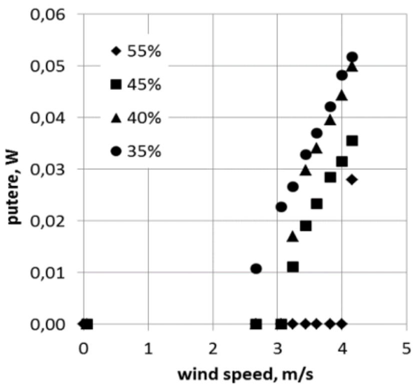

Fig. 10. *Power to the turbine shaft with the wind speed for different overlay*

When the experimental model rotates, the axle power is high when the overlay decreases and the wind speed approaches the maximum used in experiments 4.2 m/s (Figure 10).

Figure 11 shows the efficiency variations of experimental model depending on wind speed at different overlay.

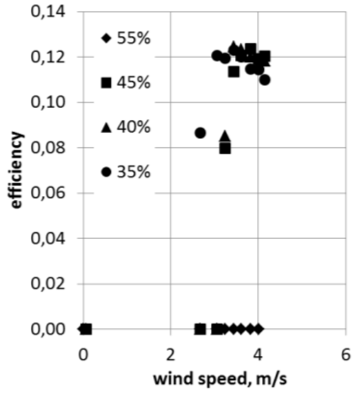

Fig. 11. *Efficiency variations of EM by wind speed for different overlapping*

Figure 12 shows the Re number values depending on specific speed of experimental model and for different overlay.

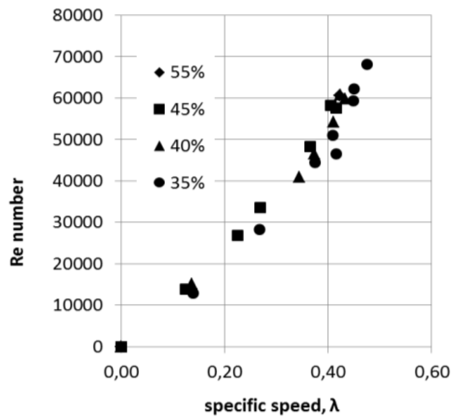

Fig. 12. *Re number values by specific speed of EM for different overlay*

Figure 13 present the efficiency variation depending on Re number and for different overlay.

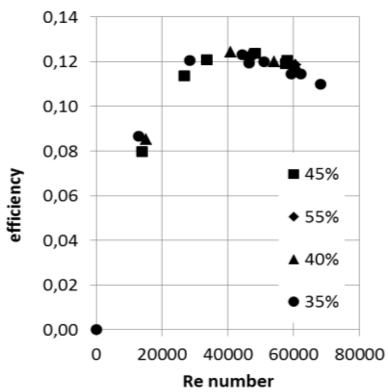

Fig. 13. *Efficiency variations of EM by Re number for EM tested in wind tunnel*

In Figure 12 it can be seen that Re number has a continuous increase with increasing of specific speed up to 70000 and the overlapping influence is small.

Efficiency calculated for the experimental model is between 0.11 and 0.13 when the Re number is between 30000 and 70000 as it can be seen in Figure 13.

4. Conclusions

Semi-spherical cups offer advantages in using them as blades for drag wind turbines that come from the sphere geometry (maximum volume at a fixed outer surface.

The conceptual model of VAWT with semi permeable cups with overlap and the distance between it and the gap was tested in laboratory conditions on a scale of 1:5 to 1:10 for wind speeds of less than 4, 2 m/s and no load. Experiments show that:

1. the existence of a wind velocity threshold for starting the rotational movement of the experimental model which increases with the increase of the overlapping of the cups.
2. for the wind speed range used (0 - 4.2 m/s), the relative speed reached about 0.5.
3. the Re number ranges from 30000 to 70000 depending on the wind speed.
4. the calculated conversion efficiency was between 0.11 and 0.13 for wind speeds of 3.0 to 4.2 m/s and is in line with the "drag-force" VAWT limit of 0.14 which is 0.14

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