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URANS flow stream in a small VAWT

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***Abstract*— Wind energy is mainly used to generate electricity and more and more with a renewable energy source character. Power production from wind turbines is affected by several conditions like wind speed, turbine speed, turbine design, turbulence, changes of wind direction, wake of previous turbines. These conditions are not always optimal and have negative effects on most turbines. The present wind turbine is a small one which allows to be used on roofs or in gardens to light small areas like publicity boards, parking, roads or for water pumping, heating... This turbine is less affected by these conditions because the blades combine a rotating movement around each own axis and around the main turbine's one. Due to this combination of movements, flow around this turbine is more optimized than classical VAWT turbines. The turbine has a rotor with three straight blades of symmetrical aerofoil. The paper presents unsteady simulations that have been performed with this turbine .It points up the influence of two different blades geometries for different rotational speeds, different blade stagger angles and different Reynolds numbers related to a wider range of wind speeds.**

***Keywords*— Numerical simulation, performance coefficient, unsteady simulation, VAWT, vertical axis, wind energy, pitch controlled blades**

I. INTRODUCTION

All wind turbines can be classified in two great families [1-3]: horizontal-axis wind turbine (HAWTs) and vertical-axis wind turbine (VAWTs). The origin of VAWT is Georges Darrieus who applied for a patent for his design in 1929. Nowadays the term Darrieus is sometimes restricted to the curved blades comparatively to the others which are referred to as "straight blades" but Darrieus's patent covers all of vertical axis rotors ([4]).

A lot of works was published on VAWTs like Savonius or Darrieus rotors [5-8] but few works were published on VAWTs with relative rotating blades [9-12].

Kiwata and al. [7], Pawsey N.C.K. [8] worked on a micro vertical-axis wind turbine with variable-pitch straight blade (during a cycle rotation) but in this turbine only blade stagger angle was variable and blades didn't rotate entirely around their own axis while they rotate around main axis of turbine. Authors show that the performance of such a turbine was better than those with fixed pitch blades and that the performance is dependent of the offset of blade pitch angle, the size of turbine, the number of blades and the airfoil profiles. The velocity wind in [7] was of 8m/s. Among those used in the present paper, this velocity was studied so comparisons with Kiwata's paper are made in this paper.

Dieudonné [9] asked for a patent in April 2006 for a turbine with rotating blades. He explained, in his site "eolprocess.com", how such a turbine works: each blade behaves like a sail on a boat which would rotate around turbine's axis. No results, like power coefficient or contours of pressure or velocity were given. In 2008, F. Penet, P. de Bodinat and J. Valette gained an innovation price for an idea in which this kind of turbine is used to make a publicity panel unlighted by wind energy. Some inventors discovered this kind of turbine in the same time on different places (Cooper P., Dieudonné P.A. M. for example [9-10]) and made studies these last ten years on this kind of VAWTs.

The present paper concerns this kind of VAWT technology in which each blade combines a rotating movement around its own axis and a rotating movement around turbine's axis. The blade sketch needs to have two symmetrical planes because the leading edge becomes the trailing edge when each blade rotates once time around the turbine's axis.

Fig. 1 shows typical power coefficient of several main types of wind turbine: VAWTs work at low speed ratios.

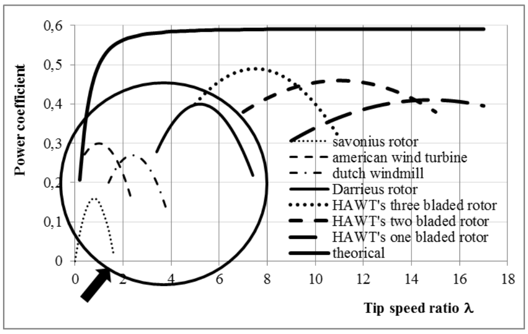

Fig. 1 Aerodynamics efficiencies of common types of wind turbines from Hau (2000).

In this paper, the benefit of rotating elliptic blades is shown: the performance of this kind of turbine is very good and better than those of classical VAWTs for some specific initial blade stagger angles between 0 and 15 degrees. It is shown that each blade's behaviour has less influence on flow stream around next blade and on power performance. The maximum mean numerical coefficient is about 38%.

Results are compared between elliptic blades and straight blades: local results like contours of pressure, velocity fields, unsteady power coefficient, mean power coefficient.

II. NON DIMENSIONAL COEFFICIENTS

The common non dimensional coefficients used for all wind turbines are:

- Efficiency of a rotor, named power coefficient C_p ,

$$C_p = P_{eff} / \left(\rho S V_0^3 / 2 \right) \qquad (1)$$

In which P_{eff} *is* the power captured by the turbine and $\left(\rho S V_0^3 / 2 \right)$ is the total kinetic energy passing through the swept area (Fig. 3).

- Speed ratio l

$$\lambda = \omega R_t / V_0 \qquad (2)$$

Where ω is the angular velocity of the turbine, R_t *is* generally the radius blade tip (radius of centre of blade in case of this paper) and V_0 the wind velocity.

- Reynolds number R_e (Marchaj C. A.) based on blade's length

$$R_e = V_0 L / \nu \qquad (3)$$

III. GEOMETRY AND TEST CASES

The sketch of the industrial product is shown in Fig. 2. Blades have elliptic or straight sketches and relatively height, so a 2D model was chosen. The calculation domain around turbine is large enough to avoid perturbations as showing in Fig. 3. Elliptic forms have minor radius of 75 mm and major radius of 525mm. Straight forms have a length of 1050 mm. Distance between turbine axis and blade axis is 620 mm.

Fig. 2 Sketch of the VAWT studied.

The model contains five zones: outside zone of turbine, three blades zones and zone between outside zone and blades zones named turbine zone. Turbine zone has a diameter named D (equal to the sum of R, plus the major radius of blade plus a little gap allowing grid mesh to slide between each zone). Except outside zone, all other zones have relatively movement. Four interfaces between zones were created: an interface zone between outside and turbine zone and an interface between each blade and turbine zone. Details of zones are given in Fig. 4 and 5.

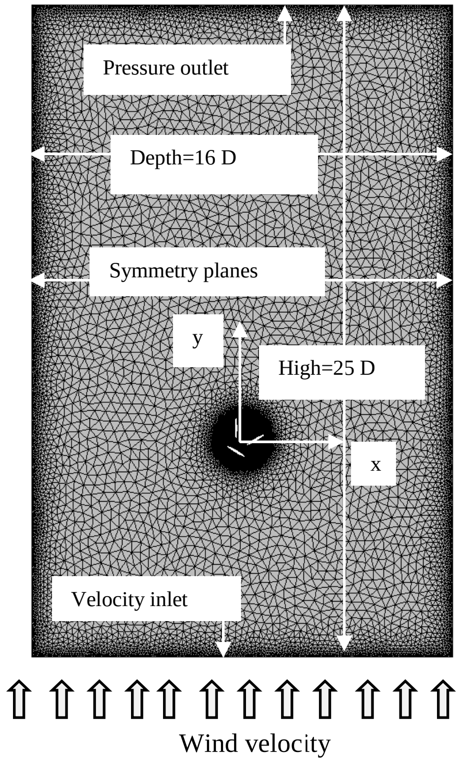

Fig. 3 Sketch of the VAWT studied.

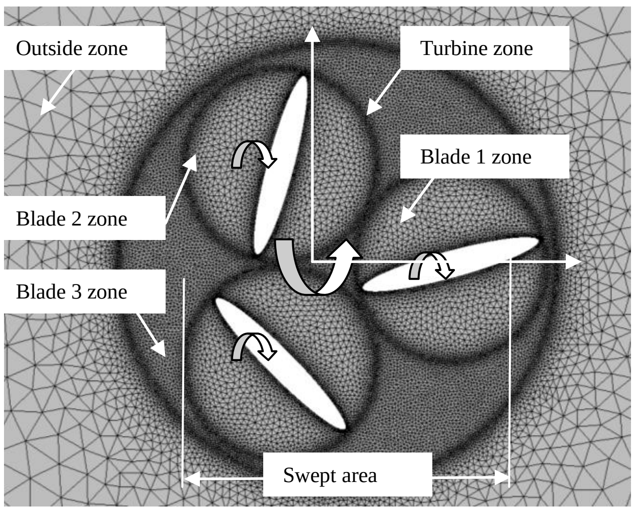

Fig. 4 Zoom of the mesh of the VAWT studied (elliptic blades).

In the present study, a blade speed ratio based on the radius corresponding to the distance between turbine's axis and blades' axis which is constant was chosen, in comparison with classical blade tip which is not constant in this kind of turbine. So in equation (2), R is the radius of the centre of each blade (620 mm).

Mesh was refined near interfaces. Prism layer thickness was used around blades. The resulting computational grid is an unstructured 2D triangular grid of about 100 000 cells, shown in Fig. 3.

Boundary conditions are velocity inlet to simulate a wind velocity in the lower line of the model (7.8e4<Re<5.6e5), symmetry planes for right and left lines of the domain and pressure outlet for the upper line of the domain.

A time step corresponding to a rotation of 6.28e-3 radians was chosen to avoid to deform more quickly mesh near interfaces and so, to avoid negative cells. So a new mesh was calculated at each time step.

All simulations were realized with Star CCM+ V8.02 code using a RANS k-ε turbulence model.

The initial blade stagger angle is the angle between blade 1 and x axis as can be seen in Fig. 5. The azimuthal angle is the angle between x axis and the segment between the centre of the domain and the centre of blade 1 region at each time.

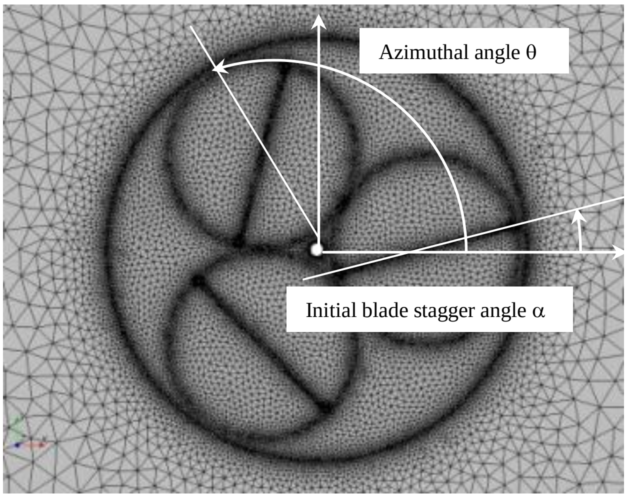

Fig. 5 Zoom of the mesh of the VAWT with straight blades

A. Elliptic blades

Calculations for four initial blade stagger angles and elliptic blades are analysed and presented here: -30, 0, 15 and 30 degrees. They are also compared to some results with Kiwata and al.

B. Elliptic and straight blades

In a first part, results for an initial blade stagger angle of 15 degrees, for a speed ratio of 0.6 and for Re equal to 560 000 are presented. Contours of pressure near turbine zone are compared between the two types of blades.

In a second part, global results like performance coefficients are compared between the two kinds of blades and for different Reynolds numbers: 77 800, 155 000, 291 000 and 560 000, for different speed ratios: 0.2, 0.4, 0.6 and 0.8 and for different blade stagger angles: -30, 0, 8, 15 and 30 degrees.

IV. Torques and power coefficient

For this kind of turbine each blade needs energy to rotate around its own axe so real power captured by the turbine has to be corrected.

Code gives torque M_t around turbine axis for each blade, pressure forces and viscosity forces. So

$$M_{ti} = \iint_{S\,bladei} \vec{OG_i} \wedge \vec{df} + \iint_{S\,bladei} \vec{G_i M} \wedge \vec{df} \qquad (4)$$

Where O is the turbine centre, G_i the axis centre of blade i and $\vec{df}$ is elementary force on the blade i due to pressure and viscosity, so

$$M_{ti} = C_{1i} + C_{2i} \qquad (5)$$

with

$$C_{1i} = C_1\, blade\, i = \iint_{S\,bladei} \vec{OG_i} \wedge \vec{df} \qquad (6)$$

And

$$C_{2i} = C_2\, blade\, i = \iint_{S\,bladei} \vec{G_i M} \wedge \vec{df} \qquad (7)$$

Real power was given by

$$P_{eff} = \sum_{i=1,2,3} M_{ti}\, \omega_1 + \sum_{i=1,2,3} C_{2i}\, \omega_2 \qquad (8)$$

With ω_1, angular velocity of turbine and ω_2 relative angular velocity of each blade around its own axis

As $\omega_2 = -\omega_1/2$ (9)

As $P_{eff} = \sum_{i=1,2,3} (M_{ti} + C_{1i})(\omega_1/2)$ (10)

And power coefficient by equation (1) in which swept area is those showed in Fig. 4 for the cases with three rotating blades

V. Results

A. Elliptic blades

1) Global results

The benefit of rotating blades has been confirmed in reference [11].

Only global results were resumed here. Figure 6 shows the power coefficient with azimuthal angle of blade 1 for the four different blade stagger angles studied. These result shows a high unsteady flow for high angle (-30 and 30 degrees) and a relatively small power coefficient but, on the contrary, results for angle of 0 and 15 degrees are very good : a good periodicity is observed and good mean power coefficients are obtained as showing in figure 7.

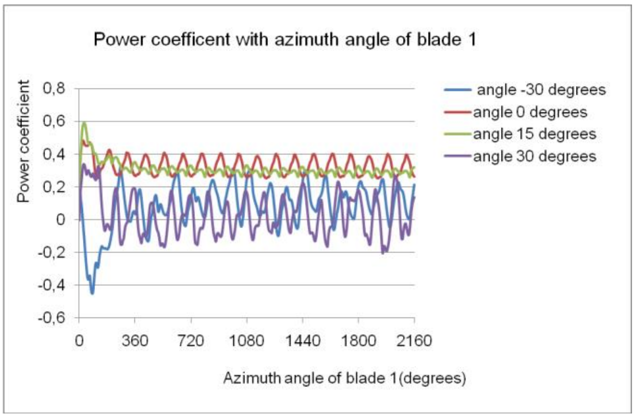

Fig. 6 power coefficient with first blade position cases b

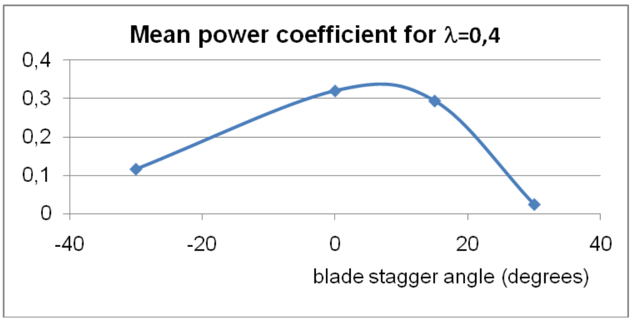

Figure 7 Mean Power coefficient with blade stagger angle for elliptic blades

2) Comparison with results of Kiwata et al's one

The present study is a numerical one so it is interesting to compare results to some other experimental. The authors have chosen to compare them to a micro VAWTs for which numerical results were published: the work of T. Kiwata and al. ([5]) was selected for this.

The VAWTs of T. Kiwata and al. is an H-Darrieus type in which passive variable pitch is tested. Two types of prototypes were tested. The present one was compared to the second prototype PT2 in which turbine diameter is 800 mm, blade span length (some equivalent of high of turbine) is 800 mm, thickness of blade is 42 mm, blade chord length 200 mm, number of blades 3, main link length (some equivalent to radius of axis of blades) is 373 mm and with quasi symmetric blades NACA634-221. The maximum mean power coefficient for the PT2 turbine was about 23% for blade offset pitch angle of 11.9 degrees with blade pitch angle amplitude of 15 degrees compared to the same turbine with fixed blade offset pitch angle of 2.4 degrees with a mean power coefficient of about 10%. Figure 7 show a mean power coefficient of about 32% for the present turbine.

B. Elliptic and straight blades

1) Contours of pressure

Fig. 8 to 11 give contours of relative pressure for elliptic blades and figures 12 to 15 give same results for straight blades for the maximum Reynolds number corresponding to a wind velocity of 8 m/s, for a speed ratio of 0.6 and for an initial blade stagger angle of 15 degrees. For these values, results are periodic with no highly instabilities. So, only results between 0 to 120 degrees are presented.

In Fig. 8 to 11, scale between -200 to 100 Pa is used; in Fig. 11 to 15 scale between -200 to 80 Pa is used. Comparisons between two kinds of profiles show quite same behavior but emphasized in case of straight blades.

For each kind of blades, a swirl arises at the leading edge of the lower blade (Fig. 8 and 12). This swirl growth when the blade rotates (Fig. 9, 10, 13 and 14). The swirl breaks off blade for azimuth angle of blade θ equal about -14 degrees and reduces until vanished for θ equal about 90 degrees. In figure 8, two swirls can be observed, the first near the leading edge which has broken off the blade and the second quite above the first which is vanishing.

As it can be observed in the previous studies, blades for azimuth angle between 90 to 250 degrees seem to slide in the flow field avoiding to disturb the flow stream of the wind and avoiding to generate a negative torque as it can be seen in the next part.

Elliptic blades

Straight blades

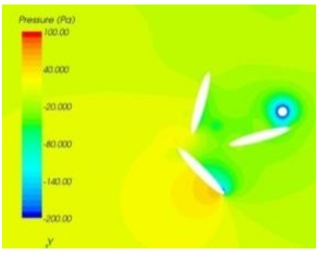

Fig. 8 θ = 0 degree

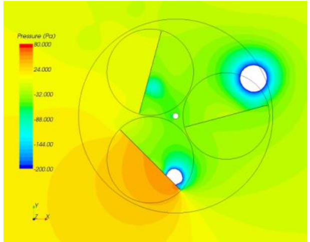

Fig. 12 θ = 0 degree

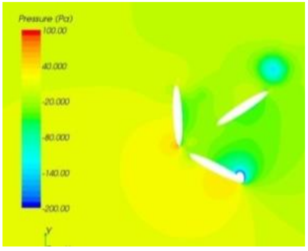

Fig. 9 θ = 36 degrees

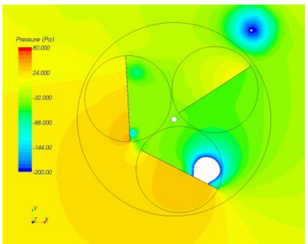

Fig. 13 θ = 36 degrees

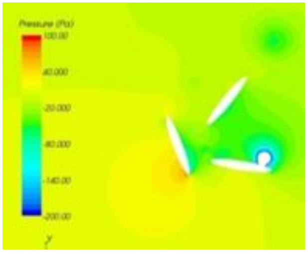

Fig. 10 θ = 72 degrees

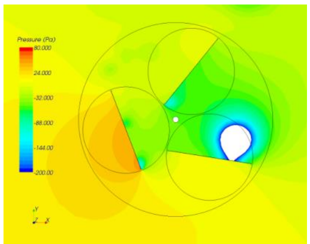

Fig. 14 θ = 72 degrees

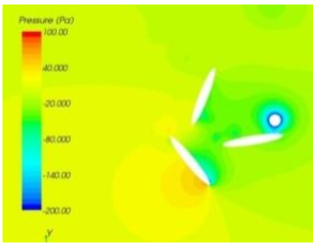

Fig. 11 θ = 108 degrees

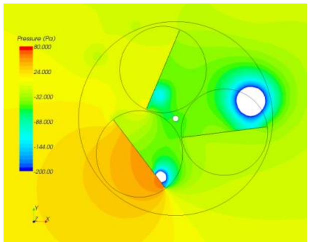

Fig. 15 θ = 108 degrees

Contours of pressure, λ = 0.6, Re= 560 000

2) Global performances

In this second part, instantaneous results are first presented to show the influence of parameters (blades geometries, initial blade stagger angles, blade speed ratios and Reynolds numbers).

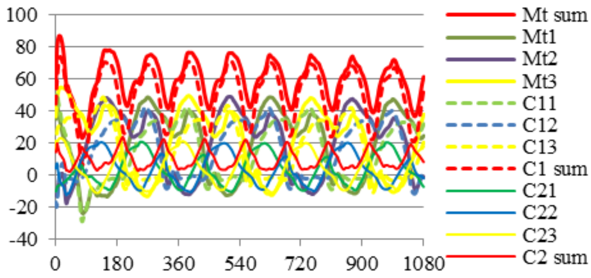

Fig. 16 Elliptic blades λ=0.2

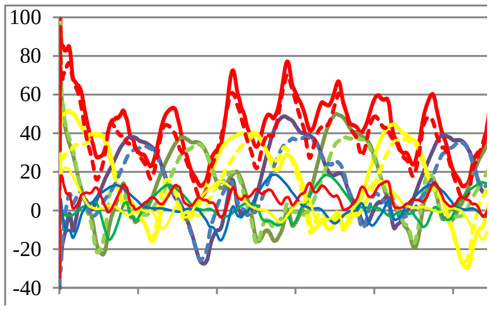

Fig. 17 Straight blades λ=0.2

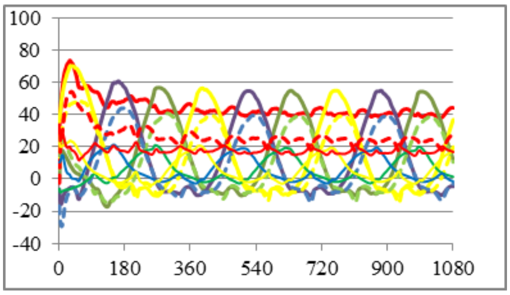

Fig. 18 Elliptic blades λ=0.4

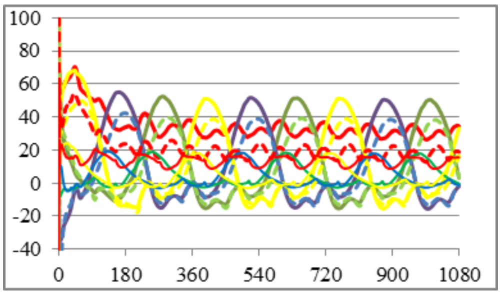

Fig. 19 Straight blades λ=0.4

Torques (mN/m) for initial blade stagger angle of 15 degrees with azimuthal angle of blade 1, Re=560 000

Fig. 16 to 19 presents evolution of torques with azimuthal angle θ of blade 1 for an initial blade stagger angle of 15 degrees and for Reynolds number of 560 000 for the two kinds of blades. Comparison between these results show that straight blades is more influenced by low and high blade tip ratio than elliptic blades: instabilities can be observed in Fig 17.

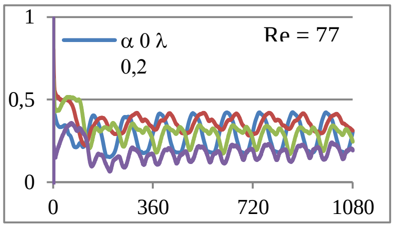

Fig. 20 Re=77 000, α=0 degree

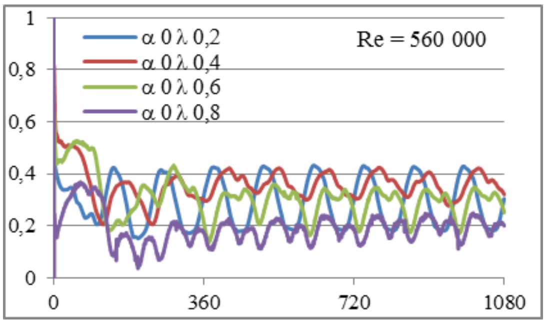

Fig. 21 Re=560 000, α=0 degree

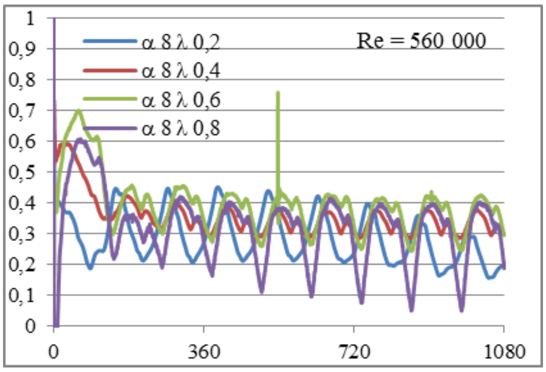

Fig. 22 Re=560 000, α=8 degrees

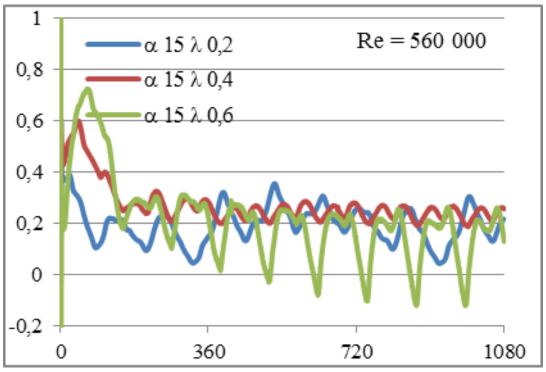

Fig. 23 Re=560 000, α= 15 degrees

Instantaneous power coefficients with azimuthal angles of blade - straight blades

Fig. 20 and 23 give instantaneous power coefficients with azimuth angle of blade 1 for straight blades. Comparison between Fig. 20 and 21 shows a very little influence of Reynolds numbers: results are quite similar.

Fig. 22 and 23 confirm that low (λ=0.2) and high (λ=0.8) blade speed ratios lead to very bad performance for straight blades: it can be observed that mean values decrease and that range of change increases, this leads to increase instabilities and to emphasis phenomenon like birth of swirls which disturb flow stream and performances of turbine.

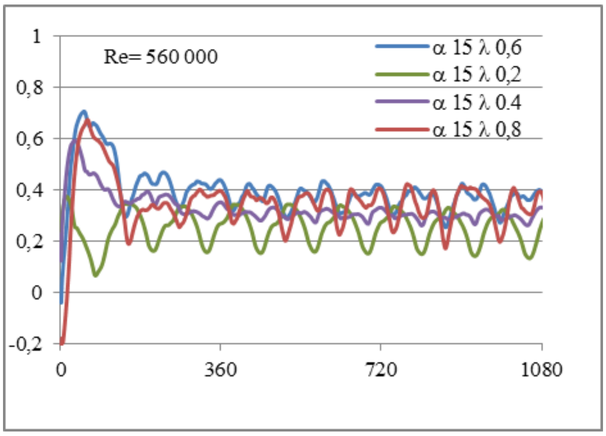

Fig 24 Instantaneous performance coefficient with azimuthal angle of blade 1 – elliptic blade

Comparison between Fig. 23 and 24 shows the disadvantage of straight blades for an initial blade stagger angle of 15 degrees: a significant decrease of power coefficient and a significant increase of range of change and of instabilities can be observed between straight and elliptic blades.

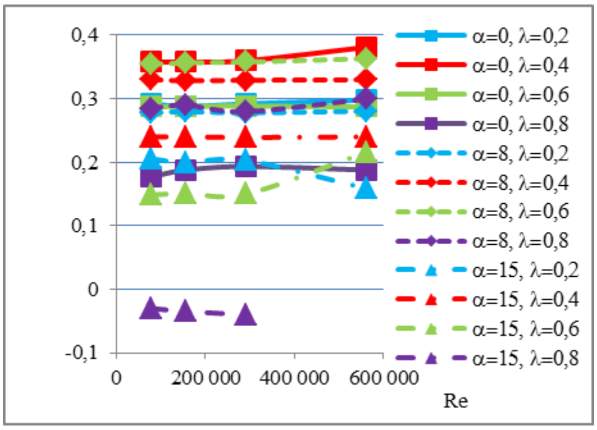

Fig. 25 Mean power coefficients for different blade stagger angles with Reynolds number-Straight blades

The low influence of Reynolds number is confirmed in figure 25 which gives mean power coefficients for different initial blade stagger angles with Reynolds numbers for straight blades. It can be observed a small increase of mean power coefficient with Reynolds number.

Finally figure 26 gives mean power coefficients for all test cases, for elliptic (EB) and straight blades (SB).

This figure summarizes all remarks already made:

Low influence of Reynolds number (same color curves but with different styles)

Bad influence of straight blades comparatively to elliptic blades for an initial blade stagger angle of 15 degrees (brown and blue curves can be compared).

Better influence of straight blades comparatively to elliptic blades for an initial blade stagger angle of 0 degree (red and pink curves can be compared). Maximum mean power coefficient is better for straight blades but it decrease quickly when blade speed ratio decrease or increase from the value 0.4

Better stability of results for elliptic profile.

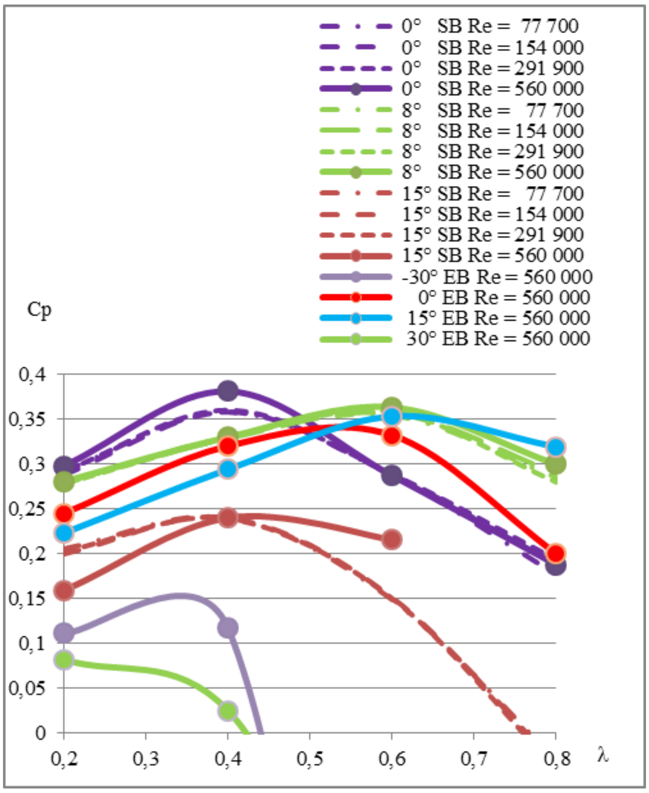

Fig. 26 Mean power coefficient for all test cases with blade speed ratios λ

VI. CONCLUSIONS

Numerical experiments were carried out to study the influence of different parameters on the performance of turbines with rotating blades; the following conclusions can be drawn:

- The performance of this kind of turbine was very good as expected and better than those of classical VAWTs for some specific blade stagger.

- Each blade behaviour seems to have less influence on flow stream around next blade and on power performance.

- The maximum mean numerical coefficient at λ=0.4 was about 32%.

A lot of work has still to be done:

- The study of influence of the number of blades to confirm that the relative rotation of blade increase the power performance because each blade doesn't disturb the next blades and to estimate for what number of blades this is right.

- The study of the influence of geometrical parameters like the radius of axis of blades, the minor and major radius of the elliptic design, the choice of this design with the consideration that each side of blade is useful for publicity

- confirm these numerical results by an experimental apparatus in an open-circuit type wind tunnel.

NOMENCLATURE

c_p	power coefficient (no units)
C_{eff}	real torque (mN)
D	diameter of turbine zone (m)
G_i	center of rotation of blade i
M_{ti}	torque of blade i by turbine axis, mN
O	center of rotation of turbine in 2D model
P_{eff}	real power
R	radius of axis of blades, =0.62 m
R_e	Reynolds number based on length of blade
R_t	radius of blade tip, m
S	captured swept area, m^2
V_0	wind velocity, =8 m/s
λ	blade or tip blade speed ratio (no units)
ρ	density of air, kg/m^3
θ	azimuth angle of blade 1(degrees)
ω_1	angular velocity of turbine (rad/s)
ω_2	angular velocity of pales (rad/s)

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