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A numerical study of the influence of solidity on the performance of vertical axis turbine

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Abstract. The paper is developed in the framework of CFD to study the performance of Vertical Axis Turbines (VAT). One direct application is to establish design trends regarding the solidity. The model is validated with benchmarks from the literature for fluvial turbine. As for turbulence models, transitional SST version of k-w is used. The model includes two additional conservation equations for intermittency and critical Reynolds that establishes the transition from laminar to turbulent. Flow pattern are analyzed at intermediate positions along the revolution. A reduction in solidity increases the operation conditions.

1 Introduction

Vertical Axis Turbines (VAT) can operate at low velocities, hence they are suitable to extract energy from both: wind and water flows. The fluid mechanic design in both cases is quite similar, the only difference is the operating condition. While wind is characterised by velocities around 7 m/s for these applications, the water velocities are in the order of 1 m/s, however, there is a slight change on the range of variation of Reynolds number when operating with air or water. In both cases, Reynolds number has an intermediate value in the transition regime between laminar and turbulent.

This collaboration of three teams from universities of Valladolid (Spain), Guanajuato and Durango (Mexico) started in 2011. Previous milestones involved the characterization of vertical axis wind turbines (VAWT) using 2D models in a non-arm configuration, some examples are:

- The influence of the twist angle variation at the chord ends in symmetric airfoils NACA0015, [1].
- The analysis of the camber effect in non-symmetric airfoils NACA2425 and NACA7425, [2-3].
- The study of the solidity of the rotor NACA 0025, [3-4].
- Influence of fixed pitch angle in NACA0015 [5-6].

The turbulence models that have a better performance in 2D simulations of VAT are the RNG k-ε used in [2-4] and the transitional SST k-ω applied with success in [5-6] and recommended by other references of the literature [7-8].

This paper is devoted to the validation of the 2D model of a three straight blades turbine type H- Darrieus, see figure 1, and the analysis of the influence of solidity on the performance of the rotor.

The manuscript is structured as follows: section 2 summarizes the main details of the numerical model (mesh, operating conditions, and turbulence model), section 3 shows the validation of the model, in section 4 the flow patterns are analysed and section 5 shows the influence of the solidity in the power coefficient curves.

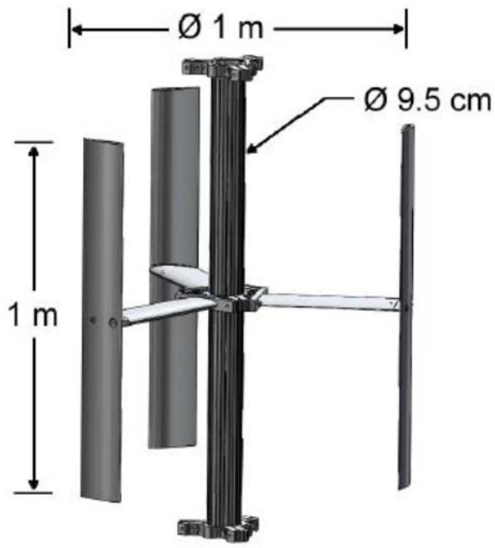

Fig. 1. Scheme of the dimensions of the UNH-RVAT [9-10].

2 Numerical model

Navier Stokes equations for two-dimensional, transient, incompressible and turbulent flow are to be solved using

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moving reference mesh in the rotor and steady mesh in its surroundings.

Equations were solved with a second order scheme. Pressure and velocity coupled resolution uses the method SIMPLE.

Temporal resolution corresponds to 600 time steps per revolution; hence it is recalculated when the rotation speed is modified.

$$\Delta T = \frac{2\cdot\pi}{\omega\cdot 600} \tag{1}$$

2.1 Boundary conditions

The geometrical details of the turbine are summarized in table 1, and the operating conditions are indicated in table 2.

Table 1. Summary of geometrical details for VAT.

Airfoil	NACA 0020
Shaft Diameter	0.095 m
Rotor Radius (R)	0.5 m
Length (b)	1 m
Chord (c)	0.136 m
Number of Blades (Z)	3
Solidity(σ)	0.4

Table 2. Summary of operating conditions for VAT.

Airfoil	NACA 0020
Density (kg/m^3)	1000
Viscosity (kg/(ms))	$1.1\ 10^{-3}$
Water Velocity (m/s)	1
Turbulence Intensity (%)	10
Averaged Reynolds no. (-)	$9.07\ 10^{5}$
Depth of the turbine (m)	1
Reference Pressure (pa)	111125

2.2 Turbulence model

Transitional SST version of the k-ω model performs adequately when the flow regime is transient between laminar and turbulent regimes [7, 8]. It solves two additional conservation equations: one for intermittency, ϒ that is the ratio of time for turbulent flow and another for the transient Reynolds number.

$$\frac{\partial}{\partial t}(\rho\Upsilon) + \mathrm{div}(\rho\vec{v}\Upsilon) = \mathrm{div}\left(\left(\mu + \frac{\mu_T}{\sigma_\gamma}\right)\mathrm{grad}(\gamma)\right) + S \tag{2}$$

$$S = P_{\gamma 1} - D_{\gamma 1} + P_{\gamma 2} - D_{\gamma 2} \tag{3}$$

The source term has different contributions of production, P, and destruction, D, of the laminar regime. Subindex 1 is related to the strain tensor whereas subindex 2 is function of control functions to establish the laminar or turbulent regime are based on 2 definitions of Reynolds number indicated in equations (4) and (5).

$$Re_v = \frac{\rho y^2 S}{\mu} \tag{4}$$

$$R_T = \frac{\rho K}{\mu\omega} \tag{5}$$

Where S is the strain tensor, ω is the turbulent frequency scale and k is the turbulent kinetic energy.

2.3 Non dimensional parameters

The performance of the turbine is expressed in terms of non dimensional parameters. The power coefficient provides information of the efficiency of the turbine, being its maximum value 59% based on the Betz theory.

Power coefficient depends on the torque T, rotation speed ω and fluid velocity V_∞, see equation (6),

$$C_p = \frac{T\cdot\omega}{\frac{1}{2}\cdot\rho\cdot v_\infty^3\cdot A} \tag{6}$$

TSR stands for Tip Speed Ratio and is defined in equation (7).

$$TSR = \frac{\omega\cdot R}{v_\infty} \tag{7}$$

Solidity was assumed to be the equation (8).

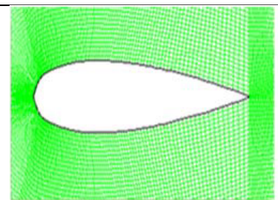
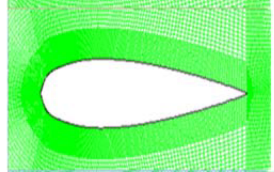
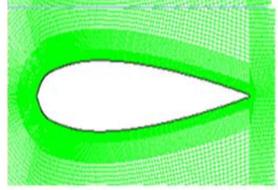
$$\sigma = \frac{Z\cdot c\cdot b}{2\cdot R\cdot b} \tag{8}$$

2.4 Sensibility to the mesh

Three different meshes are used to test that the results are independent from the spatial resolution. The main difference is the spatial resolution near the foils. Table 3 shows the number of cells of the three models as well as evidences of the quality of the mesh.

One parameter related to the mesh quality is the wall y^+ defined as a function of the friction velocity u_τ, the distance of the cell center to the wall and the kinematic viscosity. The transitional STT k-ω turbulence model requests y^+ values around the unit in order to solve the laminar boundary sub-layer.

Table 3. Details of the mesh near the blades.

Mesh	No. cells	Y$^+$	Detail of the mesh
Initial	139 kc	(7,185)	
R-1	157 kc	(3,100)	
R-2	183 kc	(1,60)	

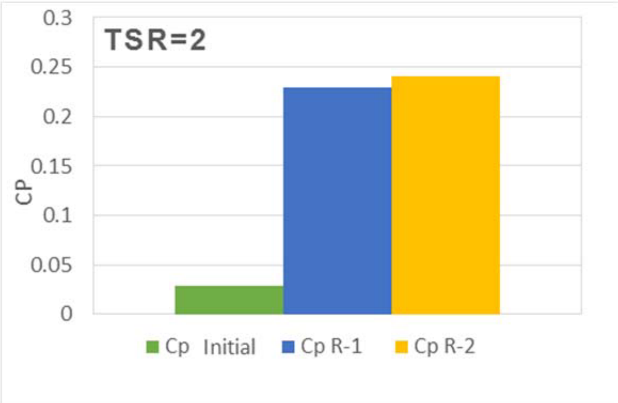


Fig. 2. Sensibility to the mesh of the peak power coefficient.

Figure 2 depicts the power coefficients for the three meshes at design operating conditions, i.e. with the TSR that provides the maximum power coefficient. Looking for a balance between precision and computational cost, any of the R-1 and R-2 meshes are suitable because of their low variance.

3 Validation of the model

The validation was carried out using the benchmark UNH-RVAT (University of New Hampshire- reference vertical axis turbine). This test case has a rotor with three blades NACA0020 and it is properly referenced by Bachant and Wosnik [9-10].

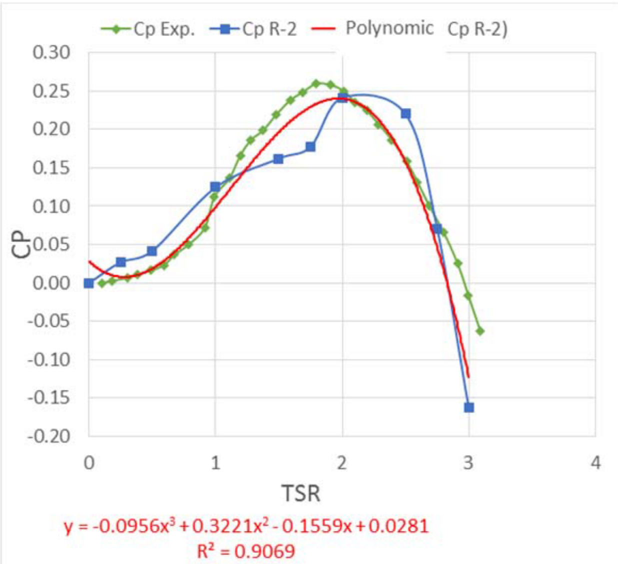


Fig. 3. Validation of the numerical power coefficient with experimental results from [9-10].

Each simulation must converge in a periodic behaviour with three periods in every revolution of the rotor. Once full periodical performance is achieved, the averaged of the instantaneous power coefficient provides one point of the characteristic curve. When modifying the rotation speed of the rotor, the curve is built up. Figure 3 shows the experimental results for the model UNH-RVAT, ref [9-10], in green diamonds as well as numerical results in blue squares.

A similar type of turbines composed by two counter-rotating rotors is the model DOE RM2 (Department of Energy - Reference Model 2) characterised at the Sandia Laboratories [11-12]. This has blades NACA 0021 and the application field is energy production from fluvial streams.

4 Flow pattern at design conditions

This section is devoted to the analysis of the flow pattern. The rotor spins counter clockwise.

Table 4. Identification of pressure and suction side of the airfoils.

Position from 12 hours in counter wise clock	High pressure side	Low pressure side
30°	External	Inner
45°	External	Inner
60°	External	Inner
75°	External	Inner
90°	External	Inner
105°	External	Inner
120°	External	Inner
195°	Inner	External
210°	Inner	External
225°	Inner	External

Figure 4 depicts the contours of pressure from the initial position with blades in locations 0º, 120º and 240º every 15º. The instantaneous flow patterns shows that the suction side (low pressure side) of the blades changes from the inner side to the outer side as indicated in table 4. As a result, the instantaneous power coefficient changes from a minimum value in location with blades at 0º, 120º and 24º, to a maximum value when blades are at 60º, 180º and 300º. The averaged power coefficient is the one represented in the characteristic curve of figure 3.

5 Influence of the solidity

When modifying the rotor radius, it is possible to modify the solidity, reducing it as the rotor radius becomes larger. Literature shows evidences of an increase of the TSR range were the turbine operates as power generator as the solidity is decreased. Also, the point in which the maximum power conditions are achieved, the design conditions, tends to appear at higher TSR. This means the turbine operates in more efficient conditions for energy generation.

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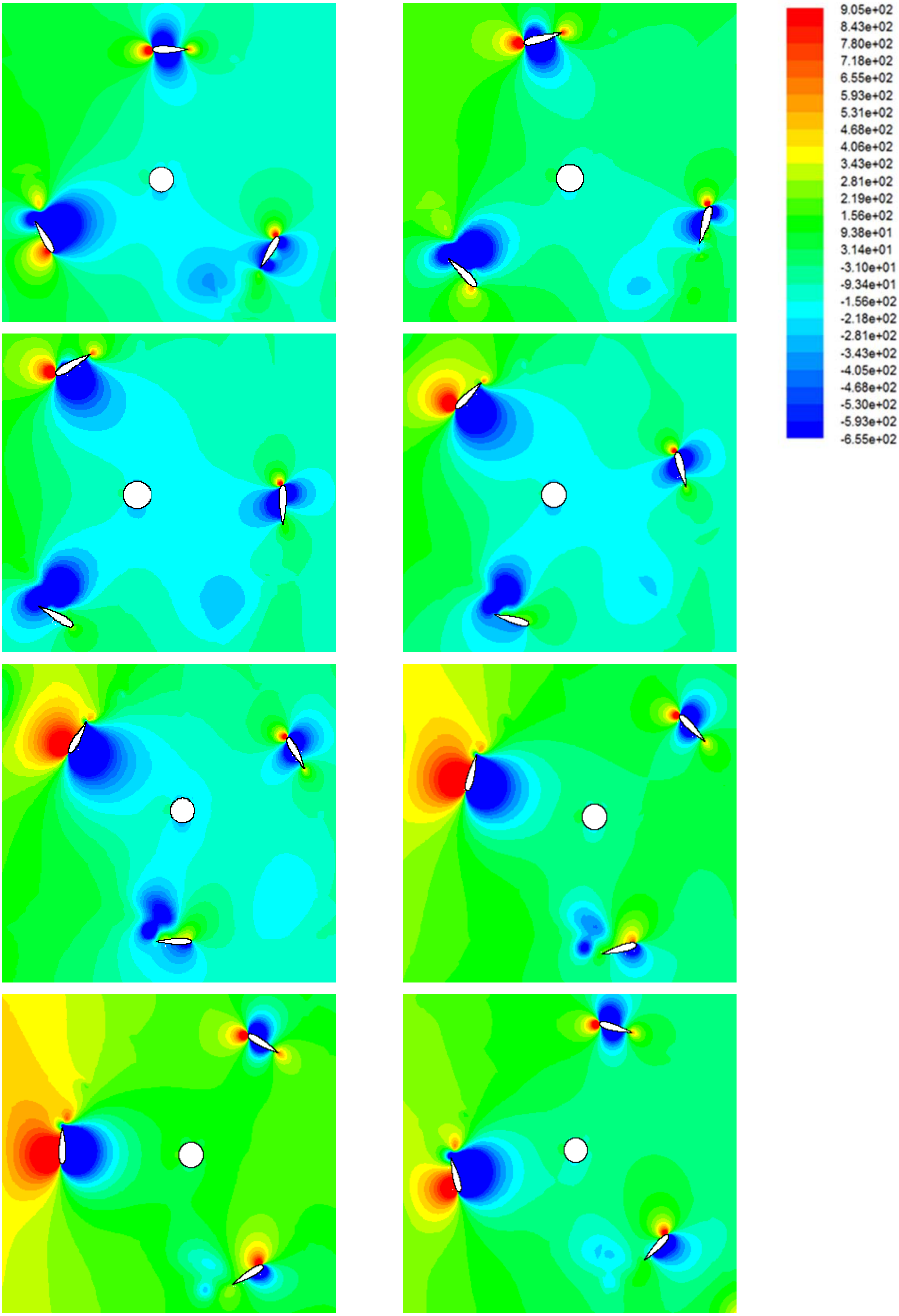

Fig. 4. Instantaneous Pressure Contours TSR = 2, every 15º.

Table 5 shows the conditions of the NACA 0020 operating as well as an estimation of the power of energy generated when operating with a flow of water of 1 m/s.

Table 5. Details design conditions at different solidities.

Solidity	**σ = 0.5**	**σ = 0.3**
TSR range	1.05 – 2.7	1 – 3.5
Cp of design	0.22	0.23
TSR of design	1.4	2.37
Power (w)	110	192

Conclusions

This work is the collaboration of three research groups: University of Guanajuato, Durango and Valladolid. The background was based on H-Darrieus operating at low wind velocities.

This work is the first one with cross turbines suitable to operate with marine currents or fluvial flows. The model is validated using the benchmark UNH-RVAT from the University of New Hampshire. It is a relatively new test case with available experimental results that allows validation of numerical models.

A simple 2D model using transitional SST k-omega model is suitable to validate with the experimental results from other sources.

A brief study of the influence of the solidity on the efficiency of the turbine has been developed, showing how in the case studied, decreasing the rotor solidity increases the operating range and the TSR of design.

Future works consider the design optimization based on different geometric parameters as solidity, pitch angle, torsion, and number of blades among others.

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