AERODYNAMIC ANALYSIS OF THE AIRFOIL OF A VAWT BY USING 2D CFD MODELLING

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Abstract

Colombia is a country where the benefits of wind power industry are barely used because of the geography in some areas does not allow the implementation of onshore horizontal axis wind turbines. Furthermore, exist rural areas without access to the electrical grid. Therefore, there is currently a deficit of energy supply in some towns. This research took place in one of those areas (i.e. Chicamocha Canyon-Santander) where the answer to the energy supply problems could be the use of vertical axis wind turbines, which can be used for turbulent flows. Hence, one task of this research is the analysis of the wind resources in the Chicamocha Canyon in order to implement the wind energy. The wind turbines must be designed in such a way that the blades take good advantage of the wind resources in the area of interest. Consequently, in the current research the analysis of two different airfoils (i.e. NACA0018 and DU 06-W-200) through a 2D CFD simulation is carried out by means of a free-software (OpenFOAM). Predicted results using the "Spalart-Allmaras" turbulence model are similar to the wind tunnel data published in the literature. Moreover, global parameters such as dimensionless lift and drag coefficients were calculated. Finally, this research encourages VAWT studies under wind turbulent flows in order to achieve the best use of natural resources in Colombia.

Keywords: aerodynamic, airfoil, blades, wind turbine, turbulence modelling, CFD.

Introduction

According to UPME*, the energy demand in Colombia in the industrial and residential sectors is going to duplicate in the next 40 years. Furthermore, 75% of the energy demand is supplied by hydroelectric power that has a negative impact on the environment [UPME (2014)]. Nowadays, there is only one wind farm that produces 19.5 MW in the country [UPME (2014)]. Nevertheless, inside Colombia wind direction change constantly due to its topography and there is the need of developing wind power solutions capable to use this variant resource in order to fulfill Colombian energy demand. The 52% of Colombian territory is not connected to the local grid and according to the government [Olaya (2012)], more than 50% of 2012 resources were invested in maintenance, installation and adequacy of outdoor lighting for rural and urban locations in Santander. This high outgoings and the importance of preserve local environment stimulates alternative energy solutions that reduce expenses of local electricity. This research is the first one in analyzing wind power density at the "Cañón del Chicamocha". It also determines the feasibility installation of Vertical Axis Wind Turbines (VAWT) at the place.

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The performance of a VAWT relies principally on its airfoil, which obtain lift or drag forces necessary to produce high efficient torque at its edge. Airfoil design and selection is an important task that depends on three main parts: wind flow conditions, airfoil shape and modelling.

Currently, Darrieus (*) VAWT (based on lift aerodynamic force) uses the commercial NACA0018 (**) airfoil. In a previous research [Claessens (2006)], a new airfoil for these turbines is developed. He presents the DU06W200 airfoil, which improves the performance of the NACA0018. The research made experiments and modelling of the airfoil based on Blade Element Momentum (BEM) theory. After that, [Castelli et al. (2012)] compared the airfoils DU06W200 and NACA0021. He evaluated their energy performance and aerodynamic forces that interact between the three wind turbine blades. The analysis was done with the commercial CFD software "Fluent 6.3.26" (***) at wind speed of 9 [m/s] (much higher than the found at the "Cañón del Chicamocha") under three different turbulence models: k-ω SST, k-ε Realizable and Spalart-Allmaras. [Chandrala et al. (2013)] analyzed the NACA0018 airfoil for horizontal wind turbines at wind speed of 32 [m/s]. He used the commercial software "ANSYS CFX" with the standard "k-E" turbulence model. Finally, [Boutilier (2011)] developed an experimental investigation of transition over the NACA0018 airfoil at a Reynolds number of $1x10^5$. He focused the work specifically at the shear layer.

This research determines experimentally the feasibility installation of VAWT at "Cañón del Chicamocha". Furthermore, the research is centered in the analysis of the airfoils DU06W200 and NACA0018 under the wind flow conditions at "Cañón del Chicamocha". The study uses CFD through the free software "OpenFOAM" (****) and the one equation turbulence RANS model developed by Spalart-Allmaras [NASA]. The difference between the airfoils can be seen at figure 1.

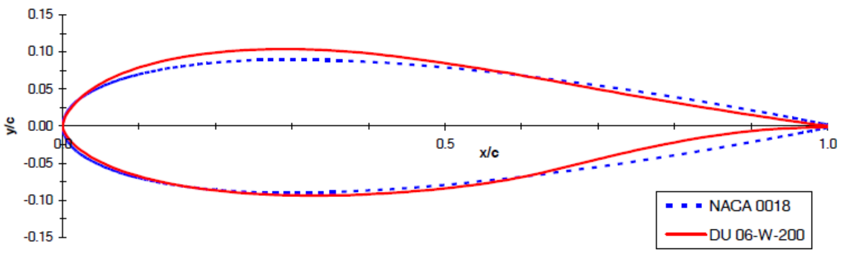


Figure 1. Comparison between airfoils NACA0018 and DU06W200 [Claessens (2006)]

(*) Darrieus VAWT´s consists of a number of curved airfoil blades mounted on a vertical rotating shaft or framework. The curvature of the blades allows the blade to be stressed only in tension at high rotating speeds[http://en.wikipedia.org/wiki/Darrieus_wind_turbine].

(**) The NACA airfoils are airfoil shapes for aircraft wings developed by the National Advisory Committee for Aeronautics (NACA). The shape of the NACA airfoils is described using a series of digits following the word "NACA". The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.[http://en.wikipedia.org/wiki/NACA_airfoil].

(***) ANSYS Fluent is a commercial software that contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer for industrial applications.[http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Fluent].

(****) OpenFOAM is a free, open source CFD software package developed by OpenCFD Ltd at ESI Group and distributed by the OpenFOAM Foundation. It has a large user base across most areas of engineering and science, from both commercial and academic organizations [http://www.openfoam.com/].

2. Methodology

Figure 2 shows the research scheme applied in this work. As it can be seen, it has two main components: an experimental, with the purpose of finding out wind potential, and the other main component, aimed to establish the best airfoil for the site under consideration.

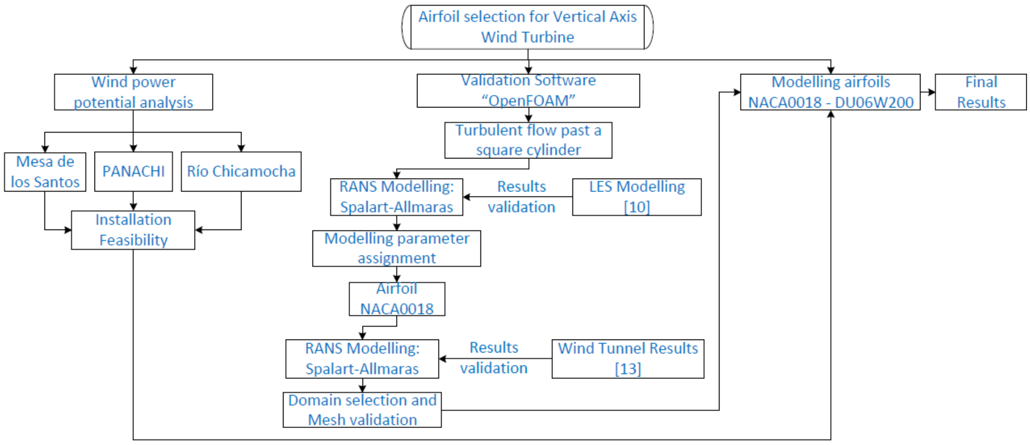


Figure 2. Research scheme.

2.1. Installation feasibility of VAWT's at "Cañón del Chicamocha"

Wind flows properties at "Chicamocha Canyon" were collected for three years, since 2009, by "Parque Nacional del Chicamocha-PANACHI" [Panachi (2012)] three times per day at three different sites: "La Mesa de los Santos", Chicamocha River and "PANACHI". By using the collected data, the feasibility installation of VAWT was analyzed. Furthermore, wind flow conditions were established in order to realize a reliable aerodynamic research of the airfoils NACA0018 and DU06W200.

Wind flow direction varies according to the topography of the selected location and VAWT does not need to be pointed towards the wind to be effective, therefore, they can be used on the sites with highly variable wind direction. Moreover, its structural and esthetic principles have improved power in turbulent flows [Castelli et al. (2012)] [Manwell et al. (2010)].

Starting from conservation of mass and the continuity equation principle, the wind potential was analyzed. The air flow as a function from air density (ρ) and its velocity (U) that pass through the swept area [A] of the turbine, can be expressed as:

$$\frac{dm}{dt} = \rho * A * U \tag{1}$$

Wind power potential can be expressed as kinetic energy in delta time:

$$\frac{P}{A} = \frac{1}{2} * \rho * U^3 \tag{2}$$

This research uses [Manwell et al. (2010)] criteria that establishes how significant wind power potential is at a selected location:

Table 1. Wind power potential criteria [Manwell et al. (2010)].

$P/A < 100\ W/m^2$	Poor
$P/A \approx 400\ W/m^2$	Good
$P/A > 700\ W/m^2$	Excellent

2.2. Aerodynamic study

Wind flow incidence over the airfoil generates force distribution over its surface, where result decomposes into lift, drag and pitching momentum as figure 3 shows.

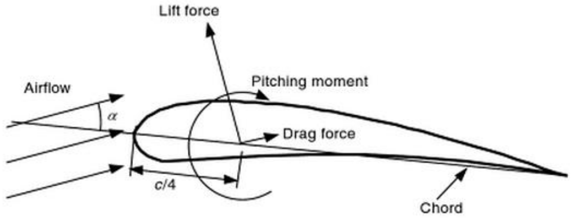


Figure 3. Forces and Momentum over an airfoil, α angle of attack c, chord length. [Manwell et al. (2010)]

These parameters are define dimensionless through its coefficients as:

Lift Coefficient: $$C_l = \frac{L/l}{\frac{1}{2}\rho U^2 c} \quad (3)$$

Drag Coefficient: $$C_d = \frac{D/l}{\frac{1}{2}\rho U^2 c} \quad (4)$$

Pitching Momentum: $$C_m = \frac{M}{\frac{1}{2}\rho U^2 A_C} \quad (5)$$

Dimensionless parameters analyze performance of airfoils under wind flow conditions of the location and through “Dynamic Similitude” concept. The mentioned parameters are function of attack angle, Mach and Reynolds number.

2.3.CFD airfoil studies

Fluid Mechanics governing equations in turbulent flow do not allow general analytic solution. Its study is approached from testing, dimensionless reasoning or mathematical simplified analysis. CFD is a new analysis technique for solving these equations and its final task is the resolution of mathematical equations that express turbulent fluid flow laws through software usage [Fernández (2012)].

Nowadays, different researches are improving airfoils performance of wind turbines through wind tunnel tests and theoretical studies. Nevertheless, these efforts are time consuming and need high technology laboratories (costly). Wind turbines CFD modelling provides affordable solutions to analyze aerodynamic issues of the airfoil and offers unlimited information over the domain since each cell modelling equals a tiny sensor for measuring each flow variable.

Governing equations in turbulent flow can be solved directly (DNS) or indirectly (INS). DNS solves each temporal and spatial fluctuation, meaning that high Reynolds numbers (10^5) require high-density meshing and short temporal steps for solving each flow vortex [Fernández (2012)], what demands high computational costs. Hence, indirect equations solving is the feasible road for problem solving. That solution has two options that employ a turbulence model for closing the equations system when a temporal average (RANS) or a spatial filtering (LES) is applied. The research at hand uses RANS and “Spalart-Allmaras” one equation model to close the equations system (Equations 6-12). This model is selected due to it was developed to analyze turbulent flows around aerodynamic surfaces. In brief, analyzed cases were make under the following conditions: incompressible, steady and turbulent flow, therefore solved equations are stationary.

Conservation of Mass:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{6}$$

Conservation of Momentum:

$$\rho\frac{\partial U_i}{\partial t} + \rho U_j\frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\mu S_{ji} - \rho\overline{u_i' u_j'}\right) \tag{7}$$

Mean strain-rate tensor:

$$s_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{8}$$

Reynolds stress tensor:

$$\tau_{ij} = -\rho\overline{u_i' u_j'} \approx \mu_t\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \frac{2}{3}\rho k S_{ij} \tag{9}$$

Kinetic turbulent energy:

$$k = \frac{1}{2}\left(\rho\overline{u'^2} + \rho\overline{v'^2} + \rho\overline{w'^2}\right) \tag{10}$$

Turbulence eddy viscosity:

$$\mu_t = \rho\hat{v} f_{v1} \tag{11}$$

Spalart-Allmaras Model:

$$\frac{\partial \hat{v}}{\partial t} + u_j\frac{\partial \hat{v}}{\partial x_j} = c_{b1}(1 - f_{t2})\hat{S}\hat{v} - \left[c_{w1} f_w - \frac{c_{b1}}{k^2} f_{t2}\right]\left(\frac{\hat{v}}{d}\right)^2 + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((v + \hat{v})\frac{\partial \hat{v}}{\partial x_j}\right) + c_{b2}\frac{\partial \hat{v}}{\partial x_i}\frac{\partial \hat{v}}{\partial x_i}\right] \tag{12}$$

2.4. OpenFOAM Modelling description

According to the properties of the flow cases, velocity-pressure coupling was solved through SIMPLE (Semi Implicit Method for Pressure linked Equations) algorithm. The research analyze fluid flow over an airfoil. The domain splits into patches where boundary conditions are established as is shown in figure 4.

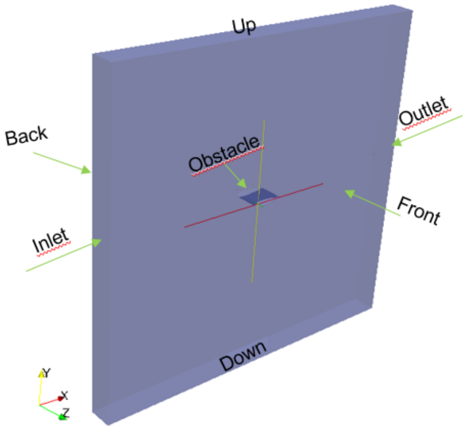


Figure 4. Patches distribution over the domain.

The domain distribution was the same for every modelling developed. There were only variations of the geometry at the "obstacle" patch and incidence flow according to the problem studied.

Previously modelling the airfoils under wind conditions from selected place, i.e. "Cañón del Chicamocha", several tests were made and compared with published results in order to verify the selected mathematical model and ensure a good implementation of the software.

2.5. *Domain definition of the Airfoil*

The appropriate domain definition ensure a develop flow downstream the airfoil and assures independence of the imposed boundary conditions. Therefore, three different domains were studied for the NACA0018 airfoil, which were implemented by [Cao (2011)], [Joukowski (2013)] and [Claessens (2006)], named hereafter as 1, 2 and 3, respectively. Domains 1 and 2 represents boundaries as function of the chord length, while the domain 3 obeys to spatial ratio of wind tunnel. Each modelling was make with an 8-block domain as is shown in figure 5.

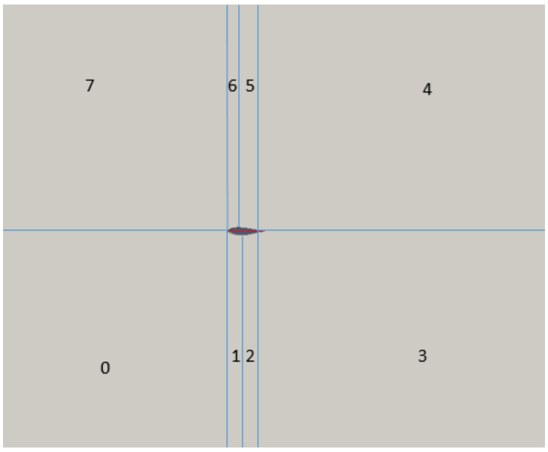


Figure 5. Domain shaped blocks in OpenFOAM.

Simulations were performed under Reynolds number of $3 * 10^5$, chord length of 60[cm], attack angle of $0°$. Furthermore, different meshes were applied in order to study its influence. The main task is find the domain that under the same flow conditions presents less computational cost, more accurate results and $y+$ acceptable values. Figure 6 shows one of the analyzed grids in detail.

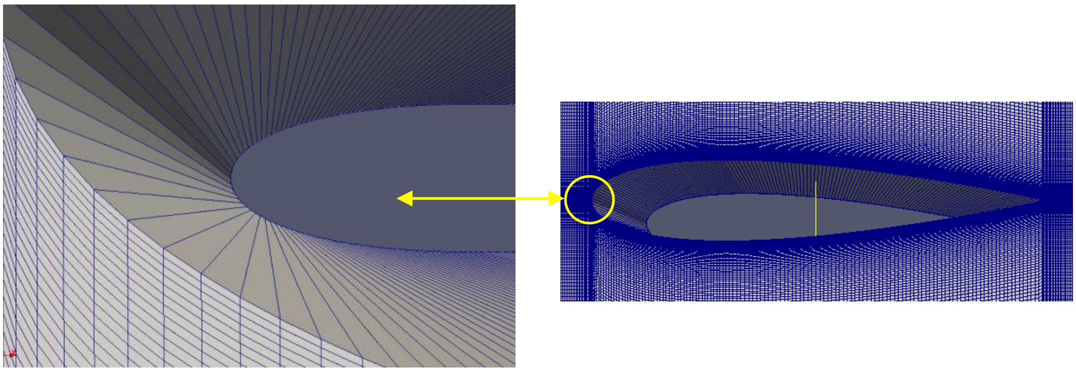


Figure 6. Mesh detail around NACA0018 airfoil.

After simulations were done, the three domains gave us these conclusions:

- Domain 1, showed convergence issues by using a high density mesh that decrease $y+$ values. Furthermore, computational cost was high. These facts made harder the study of parameters variation.
- Domain 2, allows the developing of the flow downstream at the airfoil, and its shorter dimensions reduced computational costs. Therefore, the meshing density and the $y+$ analysis were easier to run.
- Domain 3 gave a good flow resolution and its computational cost was less than domain 1. Nevertheless, wind flow direction could not be greater than 5° by the dimensions of the domain height.

Consequently, the Domain 2 was chosen to perform the simulation of the airfoils. Its geometry is formed by 5 chord lengths distance from the leading edge to the top face, 5.5 chord lengths to the bottom face, 5 chord lengths to the upwind face (inlet) and 6 chord lengths to the downwind face (outlet). The boundary conditions used at the patches shown in figure 4 are shown in table 2.

Table 2. Boundary conditions at the Patches.

Inlet	Patch
Outlet	Patch
FrontandBack	Empty
obstacle	Wall
upanddown	patch

3. Discussion and analysis of results

3.1. Wind power density analysis

Wind speed data collection from "Cañón del Chicamocha" was made with cup anemometers installed in three main parts of the location, i.e. "Mesa de los Santos", Chicamocha river and "PANACHI", above cableway supports with height of 20 [m] each.

3.1.1. "Mesa de los Santos" wind speed measuring

Average wind speed velocity has values from 5 to 7 [m/s] per year, which gives a maximum wind power density of 450$[W/m^2]$ on February and minimum of 180 $[W/m^2]$ on July. Minimum values were find between May and August as figure 7 shows.

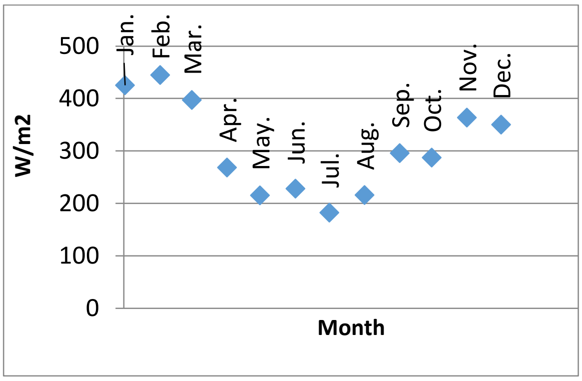


Figure 7. "Mesa de los Santos" wind power density per month.

3.1.2. Chicamocha river wind speed measuring

At this location, wind flow accelerates due to mountains that surrounds the river, which acts as a diffusor redirecting the wind to a smaller section as figure 8 shows.

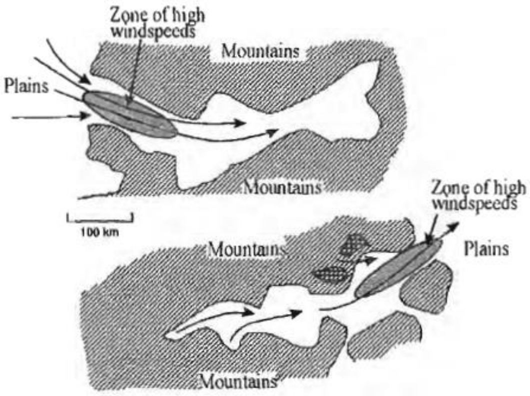


Figure 8. Wind speed increase due to canalization of prevailing winds from the mountain [Manwell et al. (2010)].

This phenomena effect is confirmed by wind speeds observed at the location, i.e. up to 8.75[m/s]. Therefore, wind power density values were up to 770[W/m^2]. Furthermore, wind speed variations were higher, as figure 9 shows.

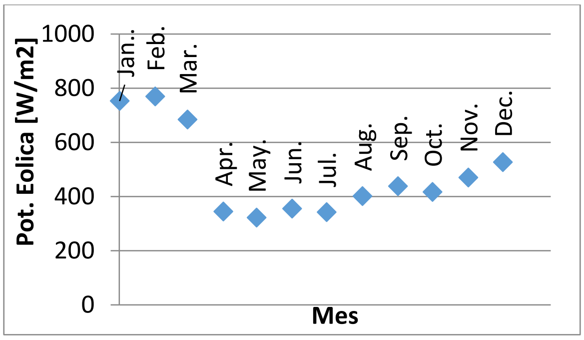


Figure 9. Wind power density at Chicamocha River per month.

3.1.3. "PANACHI" measurement

Lastly, wind flow behavior was analyzed in PANACHI, where maximum wind speed value was find in January, i.e. 5.65 [m/s], with a wind energy density of 180[W/m^2]. Figure 10 shows monthly results.

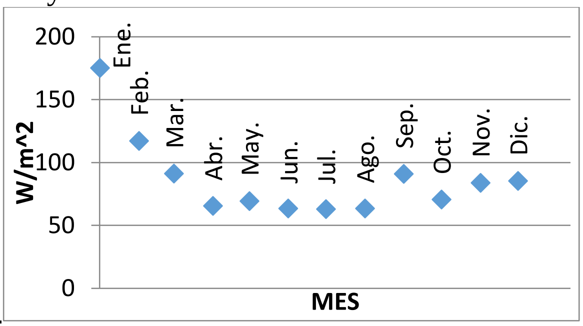


Figure 10. Average wind power density at PANACHI per month.

Table 3 summarize the annual average wind speed and wind power density of the three locations. It is shown that the greatest and feasible place for VAWT locations is at Chicamocha River.

Table 3. Wind power potential at "Cañón del Chicamocha"

Place	Annual average wind speed [m/s]	Standard Deviation	Annual average wind power density [W/m^2]
Mesa de los santos	5.974	0.736	306.188
Chicamocha River	6.928	1.084	485.115
Parque Nacional del Chicamocha (PANACHI)	4.325	0.536	86.643

3.2. Validation and verification

Obtained numerical results are validated by the lift and drag coefficients comparison against wind tunnel data from [Claessens (2006)]. Three different angles of attack of 0°, 10° and 20° were simulated for a chord length of c=0.25 [m], and Reynolds number of $3x10^5$ Results are shown in tables 4, 5 and 6, respectively.

Table 4. $y+$ results for different angles of attack.

α	$y+_{min}$	$y+_{max}$	$y+_{mean}$
0°	1.614	15.979	10.775
10°	0.636	16.436	9.58
20°	0.922	18.456	8.222

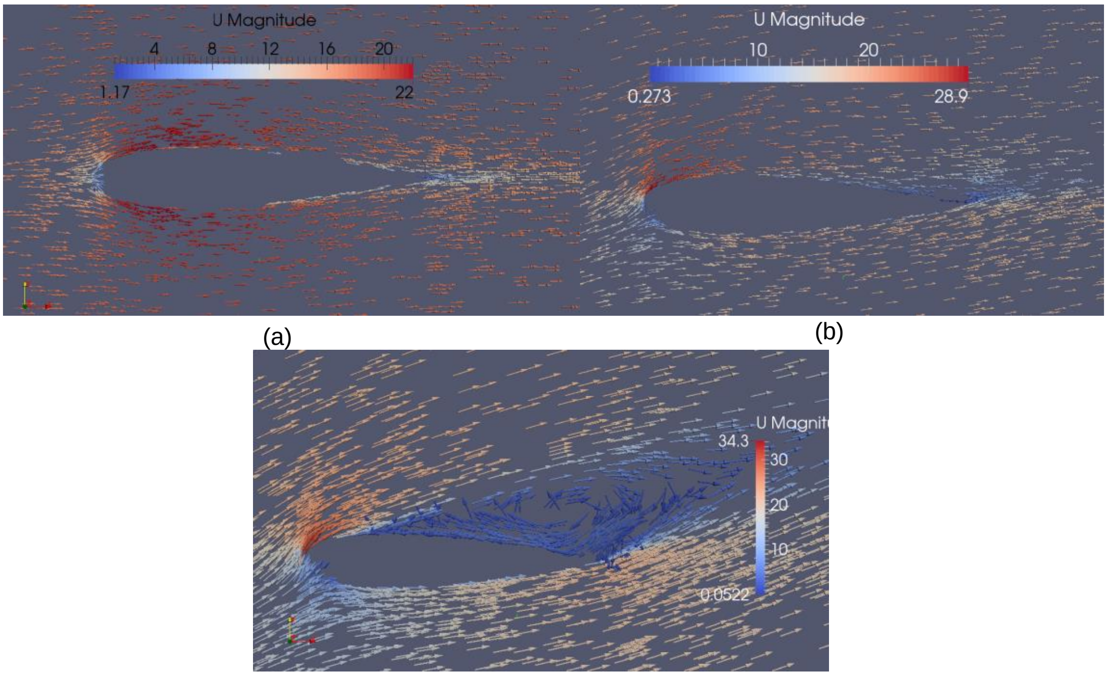
Table 5. Lift coefficients of the airfoil NACA0018 at different angles of attack.

α	$Cl_{simulacion}$	$Cl_{túnel}$	$\%Error$
0°	0.0204	0.0193	5.7
10°	0.664	0.803	17.31
20°	0.769	0.615	25

Table 6. Drag coefficients of the airfoil NACA0018 at different angles of attack.

α	$Cd_{simulacion}$	$Cd_{túnel}$	$\%Error$
0°	0.0379	0.0324	16.97
10°	0.0646	0.059	9.49
20°	0.206	0.243	15.22

According to these results, the accuracy of the implemented turbulence model is accepted. Its maximum variation was of 17% and minimum of 6% in comparison to the wind tunnel tests. The best performance of the airfoil was found at 10°, where the lift and drag coefficients ratio is the greatest, 10.3 approximately. Wind flow behavior of the airfoil NACA0018 is shown at figure 11.



(a) (b)

(c)

Figure 11. Wind velocity vectors over the airfoil at different angles of attack: (a) 0°, (b) 10°, and (c) 20°

As figure 11 shows, during an angle of attack of 0° a greater acceleration of the flow is produced around the airfoil. Whereas angles of attack lower than 20° the vortex generation is not perceivable at the trailing edge.

3.3.Analysis of the airfoils NACA0018 and DU06W200

3.3.1. Airfoil performance analysis for Reynolds numbers between $2x10^5$ and $3.4x10^5$

In order to analyze the finite volume method accuracy under Spalart-Allmaras turbulence model, simulations were carried out for the Reynolds number presented by [Claessens (2006)]. Its modelling conditions are:

- ✓ Angle of attack of 10°
- ✓ Chord length of 0.25[m].
- ✓ Fluid properties as follows:

	Re $2x10^5$	**Re $3x10^5$**	**Re $3.4x10^5$**
Wind Speed[m/s]	7.5	18	20
$\tilde{\nu}$	0.0107	0.0276	0.0306
$\boldsymbol{\nu}$	0.0107	0.0276	0.0306

A drag polar (*) was used in order to analyze the ratio between the drag and lift coefficients. Its values are show at table 7.

Table 7. Lift and drag coefficients from the airfoils NACA0018 and DU06W200 under different Reynolds numbers.

Reynolds Number	NACA0018		DU06W200	
	Cd	**Cl**	**Cd**	**Cl**
200000	0.08	0.707	0.085	0.876
300000	0.065	0.664	0.075	0.884
340000	0.07	0.687	0.077	0.926

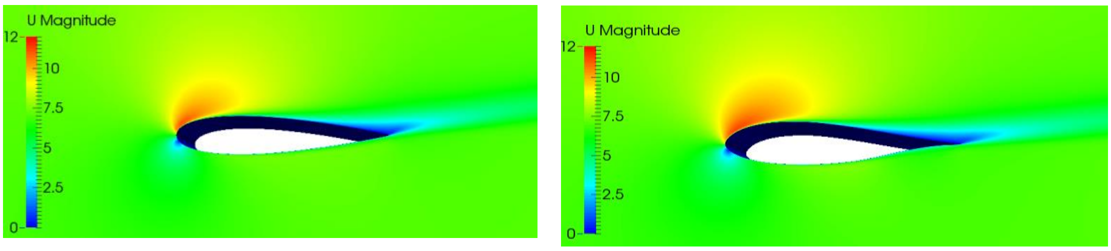
As it is shown, for the same Reynolds number the lift coefficients of the DU06W200 airfoil overcome in 23.3% the ones from NACA0018 airfoil. Furthermore, as Reynolds number increases the lift coefficient increases as well. Finally, as lift coefficients from DU06W200 airfoil are greater than NACA ones, [Claessens (2006)] results are confirmed.

3.3.2. Airfoils modelling under "Cañón del Chicamocha" wind flow

Parameters and conditions:

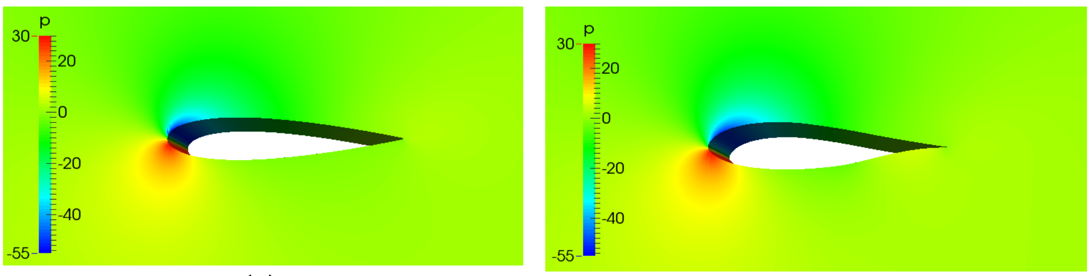
- ✓ Wind speed at the entrance is the highest found at the selected location.
- ✓ Steady state regime.
- ✓ Angle of attack of 10°.
- ✓ c=0.25[m] and $Re = 1.19x10^5$.

Predicted results are shown in figures 12 and 13.



(a) (b)

Figure 12. Wind speed average magnitude: (a) NACA0018 and (b) DU06W200



(a) **(b)**

Figure 13. Pressure distribution at airfoils (a) NACA0018 and (b) DU06W200.

(*) The **Drag Polar** is the relationship between the lift and the drag coefficient.

As it is shown in figure 12, the wind speed at the leading edge of the airfoil DU06W200 is greater than that for the NACA0018. This effect shows the design optimization of the airfoil developed by [Claessens (2006)]. Therefore, the cambered airfoil DU06W200 generates a high-pressure peak followed by a sharp fall of its values, as figure 13 shows. This phenomenon generates turbulent flow in advance quickly since the boundary layer cannot follow this pressure increase [Claessens (2006)].

On the other hand, simulation results show that NACA0018 separation bubbles at the leading edge is greater than at DU06W200 airfoil. The increase of the laminar separation bubbles leads to develop a longer wake, which is directly linked to noise production from the blades [Claessens (2006)].

The effects of these airfoils characteristics are represented by the lift and drag coefficients, which are presented in table 8.

Table 8. Lift and drag coefficients of the airfoils NACA0018 and DU06W200 under "Cañón del Chicamocha" wind flow

AIRFOIL	Cl	Cd
NACA0018	0.707	0.0801
DU06W200	0.876	0.0853

The results show a 20% increase of the lift coefficient generate by DU06W200 airfoil, at cost of a 6% increase at its drag coefficient. Thus, the airfoil DU06W200 has a better performance than the airfoil NACA0018 under feasible wind flow conditions of the location, i.e. Chicamocha River.

Conclusions

- ✓ The implementation of Vertical Axis Wind Turbines is feasible at Chicamocha river, where average wind speed is 7 [m/s] and average wind power density is 485.115[W/m^2].
- ✓ An airfoil domain with 5 chord lengths distance from the leading edge to the top face, 5.5 chord lengths to the bottom face, 5 chord lengths to the upwind face (inlet) and 6 chord lengths to the downwind face (outlet), allows a proper development of the wake using the Spalart-Allmaras turbulence model.
- ✓ Contrasted to the airfoil NACA0018, the new airfoil DU06W200 presented this results:
    - It has a lift coefficient increase of 20% with the same drag loses for NACA0018 at Chicamocha River wind speed.
    - There is a less wind flow recirculation at the trailing edge, which confirmed noise reduction of the DU06W200 airfoil.
    - Lift coefficients for the DU06W200 airfoil at Reynolds numbers between $2x10^5$ and $3.4x10^4$, are 23% greater than the NACA0018 ones.
    - Therefore, the most appropriate airfoil for blades of a vertical axis wind turbines under wind flows of Chicamocha's canyon is the DU06W200.

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