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Chicamocha canyon wind energy potential and vawt airfoil selection through CFD modeling

Energía eólica del cañón del Chicamocha y selección del perfil aerodinámico para una VAWT usando CFD

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Abstract

Large parts of the Colombian territory are not connected to the country’s electrical grid, evidencing the need for a more distributed power generation model. The use of vertical axis wind turbines (VAWT) could tackle this energy distribution problem. The present research experimentally analyzes the wind resource of a place known as Chicamocha’s canyon in Santander. Furthermore, once mean wind speed is determined, performance of two different airfoils (i.e. NACA0018 and DU06W200) under these wind conditions is assessed. The 2D CFD modeling is carried out in OpenFOAM using the “Spalart-Allmaras fv3” turbulence model. Aerodynamic airfoil behavior is evaluated in terms of global parameters such as lift and drag coefficients. This research shows the feasibility of using wind energy at the location studied where the average year density power is $485 \ [W/m^2]$, and the airfoil DU06W200 is suggested to be used for constructing the blades of a VAWT as it develops 20% more lift than the commonly used NACA0018.

Keywords: wind, energy, airfoil, DU06W200, CFD, Colombia.

Resumen

Una gran extensión del territorio colombiano no está conectado a la red eléctrica demostrando la necesidad de tener fuentes de generación alternas de energía. El uso de turbinas eólicas de eje vertical podría aportar a la solución de este problema. La presente investigación analiza experimentalmente el recurso eólico del Cañón del Chicamocha-Santander. Además de obtener la velocidad del viento promedio del sitio se caracteriza el desempeño de dos perfiles aerodinámicos, i.e. NACA0018 y DU06W200, mediante simulación 2D en CFD. Esta se llevó a cabo en OpenFOAM utilizando el modelo de turbulencia “Spalart-Allmaras fv3”. El desempeño aerodinámico es evaluado por medio de los coeficientes de sustentación y arrastre. Esta investigación muestra la factibilidad de usar energía eólica en el Cañón del Chicamocha, en donde la densidad de potencia eólica promedio anual es de $485 \ [w/m^2]$ y se sugiere utilizar el perfil aerodinámico DU06W200 para construir los alabes de una turbina eólica, ya que éste produce 20% más sustentación que el perfil NACA0018.
Introduction

According to UPME (*) [14], the 52% of Colombian territory is not connected to the local grid and the energy demand is going to duplicate in the next 40 years. Furthermore, 75% of the energy is supplied by hydroelectric power that could have a negative impact on the environment [14]. Nowadays, there is only one wind farm that produces 19.5 MW in the country [14], but the wind direction changes constantly due to Colombian topography. So, there is a need of developing wind power solutions capable of using this fluctuating resource in order to have a diversified energy portfolio for the energy demand. This research is the first one in analyzing the wind power density at the Chicamocha’s canyon, the second largest canyon worldwide, which needs to improve its surroundings infrastructure to promote tourism [15]. Because of the canyon topography, the grid there is not stable, and hotels, roads illumination, and local community need a sustainable source of energy that does not impact the environment, ensuring a sustainable growth in the tourism industry. Therefore, one of the main purposes of this research is to determine the feasibility for installing Vertical Axis Wind Turbines (VAWT) there.

The performance of a VAWT relies principally on its airfoil, which generates lift and drag forces that take advantage of the wind kinetic energy to produce torque at the shaft of the turbine. Airfoil design and selection is an important task that depends on three main topics: wind flow conditions, airfoil shape, and modeling. Currently, Darrieus VAWT(*) (based on lift aerodynamic force) uses the commercial NACA0018(**) airfoil. A previous research [5] developed a new airfoil for these turbines: the DU06W200 airfoil, which overcomes the aerodynamic performance of the NACA0018. In that work, experiments and modeling of the airfoil based on Blade Element Momentun (BEM) theory are proposed. Nevertheless, the Reynolds numbers analyzed are higher than those observed in the Chicamocha’s Canyon. Furthermore, the drag coefficient calculated through their developed software, RFOIL, overestimates the experimental values. Then [3] compared the airfoils DU06W200 and NACA0021 in terms of energy performance and aerodynamic forces. The analysis is done with the commercial Computational Fluid Dynamics (CFD) software “Fluent 6.3.26” for a $Re = 5.3 \times 10^4$ and they applied the “k-ε Realizable” [13] turbulence model. However, a validation of the turbulence model is not presented, the pressure coefficient distribution is not conclusive and nor lift or drag values are presented. The NACA0018 airfoil has been studied previously too for wind turbines, e.g. [4] analyzed that airfoil performance for horizontal wind turbines at the wind speed of 32 [m/s], but the application differs from the one this research is looking.

(*) Unidad de planeamiento energético de Colombia (The Mining and Energy Planning Unit of Colombia).

(*) 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].
Also experimental tests were conducted, e.g. [1] developed an experimental investigation of transition over the NACA0018 airfoil at a Reynolds number of $1 \times 10^5$ and they focused specifically on the shear layer distribution. Other CFD simulations of the NACA0018 airfoil are available too e.g. [7], [12] and [9], but the Reynolds numbers analyzed are not in the range of the Chicamocha’s canyon needs. The [17] research fits in the range of interest of the current research but only one angle of attack is analyzed. Therefore, this research complements the previous studies by increasing the range of Reynolds numbers analyzed for the DU06W200 airfoil, providing further information about the aerodynamic global coefficients and analyzing the performance of both airfoils under different attack angles.

This work has a double purpose. First, the feasibility of installing VAWT at Chicamocha’s canyon. Second, the analysis of the airfoils DU06W200 and NACA0018 under the wind flow conditions found at Chicamocha’s canyon. The present study applies a CFD numerical approach by means of the free software “OpenFOAM”. Turbulence is solved by the one equation RANS model developed by Spalart-Allmaras [11]. The geometry for the airfoils studied can be seen in Figure 1.

2. Methodology

Figure 2 shows the research scheme applied in this study. The work is composed by two components: first, a wind density potential study of the Chicamocha’s canyon and second, a CFD modeling aimed to compare the airfoils performance under realistic conditions to suggest one for the VAWT’s blades.
2.1. Installation feasibility of VAWT’s at Chicamocha’s canyon

The Chicamocha’s canyon national park, known as “PANACHI”, monitor constantly the wind velocity at the canyon to control the cableway safety installed at the location. The administration of the park provided to this research the historical of the data from the year 2009 up to 2012. It possesses the wind velocity magnitude at the places known as “Mesa de los Santos”, “Chicamocha’s River” and “PANACHI” (Figure 3). The historical includes daily information at three schedules: 8:00 am, 12:00 pm and 5:00 pm.

By using the collected data, the feasibility of installing a VAWT is analyzed. The topography at the canyon makes VAWT use feasible as these turbines does not need to be pointed towards the wind direction to be effective. Moreover, its structural and aesthetic principles have improved power generation in turbulent flows [3] [10].

The wind energy potential is analyzed by using the mass conservation principle:

\[
\frac{dm}{dt} = \rho \ast A \ast U
\]  

(1)
where \( \rho \) is the air density, \( U \) the velocity and \( A \) is the swept area. Then, the wind energy potential, \( P \), can be expressed as kinetic energy per time unit as:

\[
P \frac{A}{A} = \frac{1}{2} \rho U^3
\]  

(2)

In this research the criterion presented in [10] is taken into account to establish how significant the wind energy potential is at a selected location:

<table>
<thead>
<tr>
<th>( P/A )</th>
<th>Wind Power Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P/A &lt; 100 \text{W/m}^2 )</td>
<td>Poor</td>
</tr>
<tr>
<td>( P/A \approx 400 \text{W/m}^2 )</td>
<td>Good</td>
</tr>
<tr>
<td>( P/A &gt; 700 \text{W/m}^2 )</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

2.2. Aerodynamic study

The wind flow incidence over the airfoil generates a force distribution along its surface, which can be decomposed into lift and drag force (Figure 4).

![Figure 4. Forces and Momentum over an airfoil, \( \alpha \) angle of attack, \( c \) chord length [10].](image)

These parameters are defined through their dimensionless coefficients: Lift coefficient, \( c_l \), and drag coefficient, \( c_d \) :

\[
c_l = \frac{L/l}{\frac{1}{2} \rho U^2 c}
\]  

(3)

\[
c_d = \frac{D/l}{\frac{1}{2} \rho U^2 c}
\]  

(4)

Where \( L/l \) and \( D/l \) indicate the lift and drag force per unit span of the wing respectively and \( c \) the chord of the airfoil. By using the Dynamic Similitude concept [10] the airfoils performance depends on the attack angle, the Mach and the Reynolds numbers.

2.3. CFD airfoil studies
Different researchers have improved airfoil’s performance for wind turbines by means of wind tunnel tests and theoretical studies [1] [17]. Nevertheless, these efforts are time-consuming and need high technology laboratories [10]. Therefore, the use of simulation tools has become crucial to the development of a wide range of technologies. For fluids, the use of CFD has increased notoriously in the past decades because the modeling of the flow allows the analysis of microscopic scales that can not be easily captured in experimental tests.

Fluid flows are governed by the Navier Stokes equations (mass conservation and momentum):

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0
\] (5)

\[
\frac{\partial}{\partial t}[\rho u] + \nabla \cdot (\rho uu) = -\nabla p + \nabla \cdot [\mu(\nabla u + (\nabla u)^T)] + f_b
\] (6)

These equations are nonlinear and can be handled by adopting an iterative approach. Nevertheless, there is an issue that cannot be addressed directly with the numerical solution of the general transport equation: an explicit equation for computing the pressure field that appears in the momentum equation is unavailable. Moreover, solving general fluid flows requires an algorithm that can deal with the pressure-velocity gradient coupling.

In the present research the flow is assumed to be steady and incompressible, therefore the continuity and momentum equations (written in conservative form) are given by:

\[
\nabla \cdot u = 0 \tag{7}
\]

\[
\rho(\nabla u)u = -\nabla p + \mu \nabla \cdot (\nabla u + (\nabla u)^T) \tag{8}
\]

The turbulence regime is present at the current research and it can be solved via Direct Numerical Simulation (DNS) or via Indirect Numerical Simulation (INS). The DNS solves each temporal and spatial fluctuation scale of the vortex energy cascade, but the computational cost is large enough to make it unfeasible for solving industrial applications due to the high-density meshing and short temporal steps needed [6] [16]. On the other hand, an INS applies either a temporal averaging (RANS) or a spatial average fluctuation, to model the vortex generation and uses a turbulence model to close the system of equations. That make INS use feasible for industrial applications as it is needed in the current research. A RANS filtering is used to the governing equations, which leads to:

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{9}
\]

\[
\rho \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \bar{u}_i \bar{u}_j \right) \tag{10}
\]

The unknown term \(\rho \bar{u}_i \bar{u}_j\) is the Reynolds stress tensor and represents correlations between fluctuating velocities. To model that term, the “S-A fv3” turbulence model is selected due to
literature recommendations [6] and a turbulence model validation described in section 3.4.1. The S-A fv3 turbulence model is described as follows:

\[-u_i'u_j' = 2\nu T_{ij}\]

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

\[v_t = \mu_t/\rho \Leftrightarrow \mu_t = \rho \hat{\theta} f_{v1}\]

\[
fv1 = \frac{X^3}{X^3 + c_{v1}^3}
\]

\[X = \frac{\hat{\theta}}{v}\]

\[\hat{S} = fv3 \Omega + \frac{\hat{\theta}}{k^2} f_{v2}\]

where \(\Omega = \sqrt{2W_{ij}W_{ij}}\) is the vorticity magnitude and \(d\) the distance to the nearest wall. Finally, is given:

\[fv2 = 1 - \frac{X}{(1 + X/c_{v2})^3}; f_w = g \left[ 1 + c_{w3}^6 \right]^{1/6}\]

\[g = r + c_{w2}(r^6 - r); r = \min \left[ \frac{\hat{\theta}}{Sk^2 d^2}, 10 \right]\]

\[ft2 = c_{t3} \exp(-c_{t4} X^2); W_{ij} = \frac{1}{2} \left( \frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i} \right)\]

\[fv3 = \frac{(1 + xf_{v1})(1 - fv2)}{x}\]

\[c_{v2} = 5\]

By using the Finite Volume Method (FVM), the partial differential equations representing conservation laws (eq. 9-10) are transformed into discrete algebraic equations. The FVM is considered as a conservative method as the flux entering into a given volume is identical to the outflow of the adjacent volume. In addition, it can be formulated at unstructured polygonal meshes as the unknown variables are evaluated at the centroids of the volumes and not at their faces. The method starts with the discretization of the geometric domain, i.e. divide the domain into non-overlapping finite volumes. Then, the partial differential equations are discretized into algebraic equations by its integration over each discrete volume. Finally, the system of algebraic equations is solved to compute the dependent variable at each of the control volumes. By using this FVM method, some terms in the conservation equation are turned into fluxes evaluated at the faces of the finite volumes. The discretized form of the momentum and mass conservation are:
\[
\sum_{f \sim nbc(C)} \dot{m}_f = \dot{m}_e + \dot{m}_w = 0 \tag{22}
\]

\[
a_e u_e^* = \sum a_{nb} u_{nb}^* + b + (p_e^* - p_e^f)A_e
\]

\[
a_n v_n^* = \sum a_{nb} v_{nb}^* + b + (p_n^* - p_n^f)A_n
\]

\[
a_t w_t^* = \sum a_{nb} w_{nb}^* + b + (p_t^* - p_t^f)A_t \tag{23}
\]

Equation 23 can be solved only when the pressure field is given or estimated. Unless the correct pressure field is employed, the resulting velocity field will not satisfy equation 23. So, an initial velocity field \((u^*, v^*, w^*)\) is calculated based on a guessed pressure distribution \((p^*)\) to start the iterations. Then, a new value of pressure \((p)\) is updated from:

\[
p = p^* + p'
\tag{24}
\]

where \(p'\)

\[
a_{c,c} p'_{c,c} = a_{E,c} p'_{E,c} + a_{W,c} p'_{W,c} + a_{c,N} p'_{c,N} + a_{c,S} p'_{c,S} + b_{c,c} \\
a_{c,c} = a_{E,c} + a_{W,c} + a_{c,N} + a_{c,S} \\
a_{E,c} = (\rho d A)_{E,c} \\
a_{W,c} = (\rho d A)_{W,c} \\
a_{c,S} = (\rho d A)_{c,S} \\
b'_{I,J} = (\rho u^* A)_{W,c} - (\rho u^* A)_{E,c} + (\rho v^* A)_{c,S} - (\rho u^* A)_{c,N} \tag{25}
\]

Once the pressure is updated, the velocity is corrected:

\[
u_e = u_e^* + d_e (p'_e - p'_E) \tag{26}
\]

\[
v_n = v_n^* + d_n (p'_p - p'_N) \tag{27}
\]

\[
w_t = w_t^* + d_t (p'_p - p'_T) \tag{28}
\]

The described process corresponds to the Semi-Implicit Method for Pressure-Linked (SIMPLE) algorithm, which can be summarized as [6]:

a) Guess the pressure field \(p^*\).
b) Solve equation 23 to obtain \(u^*, v^*, w^*\).
c) Solve the \(p'\) using equation 25.
d) Calculate \(p\) by adding \(p'\) to \(p^*\).
e) Calculate \(u, v, w\) from their started values using the equations 26-28.
f) Solve the discretization equation for other \(\phi\)'s (such as temperature, concentration, and turbulent quantities) if they influence the flow field through fluid properties, source terms, etc.
g) Treat the corrected pressure \(p\) as a new guessed pressure \(p^*\), return to step b) and repeat the whole pressure until convergence is reached.

2.4. OpenFOAM Modeling description
Different tests are made and compared with the literature to verify the mathematical models used. The type of boundaries establish are shown in Figure 5.

<table>
<thead>
<tr>
<th>Patch</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>Patch</td>
</tr>
<tr>
<td>Outlet</td>
<td>Patch</td>
</tr>
<tr>
<td>Front and Back</td>
<td>Empty (2D modeling)</td>
</tr>
<tr>
<td>Obstacle</td>
<td>Wall</td>
</tr>
<tr>
<td>Up and down</td>
<td>Patch</td>
</tr>
</tbody>
</table>

Figure 5. Patches used at the airfoil domain [Author].

The numerical schemes are shown in Table 2. The boundary conditions and initial values of the variables are described in Table 3. Finally, the equations solvers, tolerances, and algorithms are shown in Table 4.

Table 2. Numerical time schemes used [Author].

<table>
<thead>
<tr>
<th>Mathematical term</th>
<th>OpenFOAM keyword</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell to face</td>
<td>interpolationSchemes</td>
<td>Lineal (central differences)</td>
</tr>
<tr>
<td>Component of</td>
<td>snGradSchemes</td>
<td>Corrected: does not required an explicit correction of the non-orthogonally.</td>
</tr>
<tr>
<td>gradient normal</td>
<td>gradSchemes</td>
<td>Gauss: standard discretization of the finite volumes by the Gaussian integral.</td>
</tr>
<tr>
<td>Gradient $\nabla$</td>
<td>divSchemes</td>
<td>$(\phi, U)$ bounded Gauss</td>
</tr>
<tr>
<td>Divergence $\nabla$</td>
<td></td>
<td>$(\phi, \nuTilda)$ linearUpwind</td>
</tr>
<tr>
<td>Laplacian $\nabla^2$</td>
<td>laplacianSchemes</td>
<td>Gauss linear</td>
</tr>
<tr>
<td>First and second</td>
<td>timeScheme</td>
<td>steadyState</td>
</tr>
<tr>
<td>time derivatives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. $\frac{\partial^2}{\partial t^2}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Boundary conditions at the Patches [Author].

<table>
<thead>
<tr>
<th>Boundary</th>
<th>$v_t$</th>
<th>$\bar{v}$</th>
<th>$p$</th>
<th>$u$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>$v_t = 0.0221$</td>
<td>$\bar{v} = 0.0221$</td>
<td>$\frac{\partial p}{\partial n} = 0$</td>
<td>$u = 18$</td>
</tr>
<tr>
<td>Outlet</td>
<td>$v_t = 0.0221$</td>
<td>$\bar{v} = 0.0221$</td>
<td>$p = 0$</td>
<td>$\frac{\partial u}{\partial n} = 0$</td>
</tr>
</tbody>
</table>
| obstacle      | $y^+ = u^+$ | $\frac{1}{E} \left\{ \exp(ku^+) - 1 - ku^+ 
- 0.5(ku^+)^2 - \frac{1}{6}(ku^+)^3 \right\}$ | nutUSpaldingWallFunction $y^+ = u^+$ | $\frac{\partial p}{\partial n} = 0$ | $u = 0$ |
| Front and Back| empty        |           |       |           |

Table 4. Equations solvers, tolerances, and algorithms [Author].
Table 4. Numerical time schemes used [Author].

<table>
<thead>
<tr>
<th>Description</th>
<th>OpenFOAM keyWord</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Solver Control</td>
<td></td>
<td>p GAMG</td>
</tr>
<tr>
<td>solver</td>
<td>p U nuTilda</td>
<td>smoothSolver</td>
</tr>
<tr>
<td>smoother</td>
<td>GaussSeidel</td>
<td></td>
</tr>
<tr>
<td>tolerance</td>
<td>p U nuTilda</td>
<td>1e-6</td>
</tr>
<tr>
<td>Algorithm</td>
<td>-</td>
<td>SIMPLE</td>
</tr>
<tr>
<td>Controls under-relaxation</td>
<td>relaxationFactors</td>
<td>p U nuTilda</td>
</tr>
</tbody>
</table>

3. Discussion and analysis of results

3.1. “Mesa de los Santos” wind speed measuring

The annual average wind speed range from 5 up to 7 [m/s], giving a maximum wind power density of 450 [W/m^2] on February and a minimum of 180 [W/m^2] on July (Figure 6).

![Figure 6. Monthly wind power density at “Mesa de los Santos”.](image)

3.2. Chicamocha’s river wind speed measuring

At this location, wind flow accelerates due to mountains that surround the river, which acts as a nozzle directing the wind to a smaller section (Figure 7).
This effect is confirmed by the wind speed measured at the location, with peak value of 8.8 [m/s] and wind power density of 770 [W/m²] as Figure 8 shows.

3.3. National park of Chicamocha (PANACHI) measurement

The maximum wind speed value is found in January with a value of 5.7 [m/s] and wind power density of 180 [W/m²]. Figure 9 shows the results.
Figure 9. Monthly wind power density at PANACHI.

Table 5 summarizes the annual average wind speed and wind power density of the three locations. In brief, the feasible place for VAWT locations is at Chicamocha’s river due to its high wind speed, 6.9 [m/s].

Table 5. Wind power potential at Chicamocha’s canyon [Author].

<table>
<thead>
<tr>
<th>Place</th>
<th>Annual average wind speed [m/s]</th>
<th>Standard Deviation</th>
<th>Annual average wind power density [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Mesa de los santos”</td>
<td>5.9</td>
<td>0.736</td>
<td>306.188</td>
</tr>
<tr>
<td>Chicamocha’s River</td>
<td>6.9</td>
<td>1.084</td>
<td>485.115</td>
</tr>
<tr>
<td>“PANACHI”</td>
<td>4.3</td>
<td>0.536</td>
<td>86.643</td>
</tr>
</tbody>
</table>

3.4. Validation and verification

3.4.1. Comparison between RANS and LES of turbulent flow past a square cylinder confined in a Channel

A square cylinder confined in a channel is simulated using different turbulence models to select the one that approaches the most to the literature results [8]. The influence of the mathematical simplifications and the SIMPLE algorithm are also analyzed at these tests. The domain used is shown in Figure 10.

Figure 10. Physical Configuration [8].

The fluid properties are incompressible flow, Re: 3x10³, steady state, 2D and blockage ratio of 20%. A uniform velocity profile with a thin boundary layer thickness of 6% of channel height.
is necessary to replicate the case [8]. The boundary conditions used are the same as Table 3, modifying the initial values of the variables according to the fluid properties mentioned.

A Cartesian orthogonal mesh is used and refined at the boundaries of the obstacle, i.e. cube, as Figure 11 shows. Velocity components and turbulent fluctuations are averaged in time and in the cross-stream direction.

![Structured quadrangular mesh](image1.png)

**Figure 11. Structured quadrangular mesh used [Author].**

At Figure 12, the mean streamwise velocity along the centerline is shown for different simulations varying the mesh density. The results are compared with the literature [8] (black line). This comparison is performed to find the mesh independence, which is at $5 \times 10^5$ cells, giving an average difference around 12% and standard deviation of 0.283. Therefore, the “simpleFoam” algorithm is validated for the Spalart-Allmaras fv3 turbulence model.

![Mesh independence](image2.png)

**Figure 12. Mesh independence: Mean streamwise velocity profile along the centerline (■ and black line - literature [8]).**

By using the same modeling conditions and a mesh distribution of $5 \times 10^5$ volumes, different turbulence models were analyze: k-W SST, k-E Launder-Sharma and Spalart-Allmaras fv3. The analysis shown at Figure 13, concludes that the Spalart-Allmaras fv3 keeps the most accurate distribution.
3.4.2. **DU06W200: Comparison between RANS and RFOIL simulations**

The RFOIL software used in the literature [5] based on BEM theory is compared with the present CFD results for $Re = 5 \times 10^5$, $\alpha = 0^\circ$, $c=0.25[m]$ and free transition. To ensure that develop flow reaches the airfoil, a channel length of $36c$ upwind, $44c$ downwind and a blockage ratio of 20% is designed (Figure 14).

A Cartesian orthogonal mesh is used and refined at the boundaries of the airfoil (Figure 15). Also, different meshes densities are analyzed for the Spalart-Allmaras fv3 turbulence model too (Figure 16).
The Figure 16 shows no significant variation over mesh densities of $3 \times 10^5$. The CFD results follow the pressure distribution showed by the RFOIL software with an average difference of 15%. At high Reynolds numbers, the software RFOIL has problems to predict airfoil characteristics, e.g. it overestimates the maximum lift coefficient [5]. Such variation might be presented due to the lack of accuracy found at the trailing edge of the airfoil, where the turbulence model is sensible to vortex variations. Therefore, the CFD simulations will be used as the reference model.

3.4.3. NACA0018 validation with experimental tests

The numerical results are validated by comparing the lift and drag coefficients from the literature [5]. The airfoil is simulated under three different angles of attack: $0^\circ$, $10^\circ$, and $20^\circ$. The chord length ($c$) of the airfoil is $0.25$ [m] and a Reynolds number of $3 \times 10^5$. Results are shown in Table 6, Table 7 and Table 8. The boundary conditions are the same mentioned at Table 3. The “nutUSpaldingWallFunction” provides a turbulent kinematic viscosity condition when using wall functions for rough walls, based on velocity, using Spalding's law to give a continuous nut profile to the wall ($y^+ = 0$).

Table 6. $y^+$ results for different angles of attack [Author].

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$y_{min}^+$</th>
<th>$y_{max}^+$</th>
<th>$y_{mean}^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>1.614</td>
<td>15.979</td>
<td>10.775</td>
</tr>
<tr>
<td>$10^\circ$</td>
<td>0.636</td>
<td>16.436</td>
<td>9.58</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>0.922</td>
<td>18.456</td>
<td>8.222</td>
</tr>
</tbody>
</table>

Figure 16. DU06W200 RFOIL and CFD data for $Re=5 \times 10^5$ and $\alpha = 0^\circ$ (black line: literature [5], color lines: present).
Table 7. Lift coefficients of the airfoil NACA0018 at different angles of attack [Author].

<table>
<thead>
<tr>
<th>α</th>
<th>( Cl_{simulación} )</th>
<th>( Cl_{túnel} )</th>
<th>%Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.0204</td>
<td>0.0193</td>
<td>5.7</td>
</tr>
<tr>
<td>10°</td>
<td>0.664</td>
<td>0.803</td>
<td>17.31</td>
</tr>
<tr>
<td>20°</td>
<td>0.769</td>
<td>0.615</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 8. Drag coefficients of the airfoil NACA0018 at different angles of attack [Author].

<table>
<thead>
<tr>
<th>α</th>
<th>( Cd_{simulación} )</th>
<th>( Cd_{túnel} )</th>
<th>%Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.0379</td>
<td>0.0324</td>
<td>16.97</td>
</tr>
<tr>
<td>10°</td>
<td>0.0646</td>
<td>0.059</td>
<td>9.49</td>
</tr>
<tr>
<td>20°</td>
<td>0.206</td>
<td>0.243</td>
<td>15.22</td>
</tr>
</tbody>
</table>

Wind flow behavior of the airfoil NACA0018 is shown in Figure 17.

![Wind velocity vectors over the airfoil at different angles of attack](image)

(a) 0°, (b) 10° and (c) 20° [Author].

The implemented turbulence model accuracy is acceptable, presenting a maximum variation of 17% in comparison to the wind tunnel tests. The higher performance of the airfoil is found at the attack angle of 10°, where the lift and drag coefficients ratio has the greatest value: 10.3 approximately. Figure 17 shows a greater acceleration of the flow produced around the airfoil for an angle of attack of 0°, but as the angle of attack increases, the flow separation moves towards to the leading edge at the upper surface. It produces large vortex perceivable at the angle of attack of 20° at the trailing edge, which results in higher drag.

3.5. Results
3.5.1. Airfoils NACA0018 and DU06W200: performance analysis for Reynolds numbers between $2 \times 10^5$ and $3.4 \times 10^5$

This part analyzes the Reynolds number influence on the global aerodynamic parameters of each airfoil by using the FVM under the Spalart-Allmaras turbulence model. Similar grid size is adapted to each airfoil for this study. The modeling conditions are $\alpha = 10^\circ$, $c=0.25\text{[m]}$ and fluid properties as follows:

Table 9. Wind properties established to compare the NACA0018 and DU06W200 airfoils performance.

<table>
<thead>
<tr>
<th>Wind Speed[m/s]</th>
<th>Re $2 \times 10^5$</th>
<th>Re $3 \times 10^5$</th>
<th>Re $3.4 \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{v} = 3v_\infty$</td>
<td>0.107</td>
<td>0.276</td>
<td>0.306</td>
</tr>
<tr>
<td>$v_t = \sqrt{1.5u_\infty L}$</td>
<td>0.0107</td>
<td>0.0276</td>
<td>0.0306</td>
</tr>
</tbody>
</table>

where $\tilde{v}$ is the modified turbulent viscosity and $v$ is the turbulent viscosity. The drag and lift coefficients are used in order to analyze the performance of the airfoils. The values are shown in Table 10.

Table 10. Lift and drag coefficients from the airfoils NACA0018 and DU06W200 under different Reynolds numbers [Author].

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>NACA0018</th>
<th>DU06W200</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
<td>Cl</td>
</tr>
<tr>
<td>$2 \times 10^5$</td>
<td>0.08</td>
<td>0.707</td>
</tr>
<tr>
<td>$3 \times 10^5$</td>
<td>0.065</td>
<td>0.664</td>
</tr>
<tr>
<td>$3.4 \times 10^5$</td>
<td>0.07</td>
<td>0.687</td>
</tr>
</tbody>
</table>

It can be concluded that under the same Reynolds number, the lift coefficient of the DU06W200 airfoil overcomes in 23.3% the one from the NACA0018 airfoil. As the Reynolds number increases, the lift coefficient increases too and the performance of the DU06W200 corresponds to the expectations of [5] design.

3.6. Airfoils modeling under Chicamocha’s canyon wind speed

Parameters and conditions: wind speed is the highest found at the analyzed locations, i.e. Chicamocha’s river ($u = 6.93\text{[m/s]}$), $c=0.25\text{[m]}$, $Re = 1.19 \times 10^5$, steady-state regime and $\alpha = 10^\circ$. 
Figure 18. Wind speed average magnitude: (a) NACA0018 and (b) DU06W200 [Author].

Figure 19. Pressure distribution at airfoils (a) NACA0018 and (b) DU06W200 [Author].

Figure 18 shows that wind speed at the leading edge of the airfoil DU06W200 is greater than in NACA0018. This effect shows the optimization of the airfoil developed by [5]. Therefore, the cambered airfoil DU06W200 generates a high-pressure peak followed by a sharp fall of its values, as Figure 19 shows. This phenomenon produces turbulent flow quickly since the boundary layer cannot follow this pressure increase [5].

The consequence of these airfoils characteristics are quantified at the lift and drag coefficients presented in Table 11.

Table 11. Lift and drag coefficients of the airfoils NACA0018 and DU06W200 under Chicamocha’s canyon wind speed [Author].

<table>
<thead>
<tr>
<th>AIRFOIL</th>
<th>Cl</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA0018</td>
<td>0.707</td>
<td>0.0801</td>
</tr>
<tr>
<td>DU06W200</td>
<td>0.876</td>
<td>0.0853</td>
</tr>
</tbody>
</table>

It can be concluded from the DU06W200 results, that it produces 20% more lift coefficient than the NACA0018, and the value of the drag coefficient differs only by 6%. Therefore, the airfoil DU06W200 has a better aerodynamic performance than the airfoil NACA0018 under the wind flow conditions of the location, i.e. Chicamocha’s River.

CONCLUSIONS

✓ Implementation of Vertical Axis Wind Turbines is feasible at Chicamocha’s river, where average wind speed is 7 [m/s] and average wind power density is 485 [W/m²].
The “simpleFoam” solver is validated by using the Spalart-Allmaras fv3 turbulence model by its accurate results: difference of 12% in comparison with experimental tests from the literature.

The airfoil NACA0018 shows its higher performance at an angle of attack of 10° where the lift and drag coefficients ratio has the greatest value: 10.3 approximately.

The new airfoil DU06W200 presented these results:
• Its lift coefficient increase 20% with the same drag loses as the NACA0018 airfoil at Chicamocha’s 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 $2 \times 10^5$ and $3.4 \times 10^4$, are 23% greater than the NACA0018 ones.
• Therefore, the DU06W200 airfoil shows a better aerodynamic efficiency for vertical axis wind turbines’ blades under wind properties of Chicamocha’s canyon.

FUTURE WORK

In order to complement the current studies of the wind energy potential at Chicamocha’s canyon, measurements of wind speed during night time should be done. On the other hand, analyze the incidence of wingtip vortex on the finite wings, modeling the three airfoils distribution and performing unsteady simulations of the blades is necessary to understand the physics of the phenomena and calculate the wind turbine performance. As well, the geometry of the troposkein shape for the total wing should be compared with a straight blade design.

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References


