ATMOSPHERIC TURBULENT STRUCTURE ON HILLY TERRAIN - APPLICATION TO WIND POWER GENERATION

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Abstract. *Renewable energy sources are increasingly highlighted as solutions to shortages of fossil fuels and to the degradation of socioeconomic and environmental aspects of continuing dependence on traditional fuel sources. Wind power, created by the movement of air masses, is a form of clean energy which has been progressively used in the last decades as an energy source around the world. The evaluation of a region's wind potential requires systematic work of collecting and analyzing data on the region's wind regime and its speed. The study of boundary layers is extremely relevant in determining the position of wind turbines for power generation. This paper presents a study of the development of a computational model to analyze the internal boundary layer generated inside the atmospheric boundary layer, due to a neutral wind incident at a 90º cliff and caused by the surface unevenness and significant terrain's roughness change. To describe the flows, the mass conservation, momentum and perfect gas equations are used. The computational model will be designed using the STAR-CCM+ commercial software and its results will be evaluated and compared with experimental data available in the literature.*

Keywords: *Renewable energy. Wind power. Internal boundary layer. Turbulence. STAR-CCM+.*

1. INTRODUCTION

The need to ensure diversity and security of energy supply, combined with the obligation to protect the environment, whose degradation is accentuated by traditional forms of power generation, are factors that motivated increased interest in renewable energy sources.

Wind energy is currently regarded as one of the most promising renewable energy sources known. Wind power turbines, isolated in small groups of four or five or in wind farms with fifty units, are already usual elements of the landscape of countries like USA, Germany, Denmark, the Netherlands and the United Kingdom.

In Brazil, investments to expand wind power are growing, as well as the installed wind power, especially in the states of the Northeast and in Rio Grande do Sul. Such investments are of fundamental importance in Brazil, where the wind energy potential is most intense from June to December, months with less rainfall intensity (ANEEL, 2003). This makes wind power a possible complement to power generated by hydroelectric plants, the main source of electricity in the country.

Wind energy is plentiful, renewable, clean and available in many places; it is generated by wind turbines, in which the wind is captured by propellers connected to a turbine that drives an electric generator. The amount transferred tothe power generator is a function of air density, the area covered by the blades and the wind speed, the last being the factor of greatest variability, therefore requiring a detailed knowledge of its behavior.

The wind analysis is an important step in choosing a suitable location for the installation of a wind turbine. The stronger, the more constant and more persistent winds occur about ten kilometers from the surface of the earth, but under several currently existing limitations, the space with energy potential is between thirty and two hundred meters from the ground (CRESESB, 2001). At that level the wind is directly affected by the friction on the surface, which causes changes in its speed profile.

Micrometeorological studies are of fundamental importance in many applications, ranging from course corrections in rocket launches to the improvement of thermal comfort in buildings. Such studies become even more relevant in areas where the terrain causes considerable changes in wind fields, such as coastal cliffs, vertical escarpments delimiting the meeting of the land to the sea, which are found in various locations around the world and, in Brazil, are present in the Rio Grande do Sul, Rio de Janeiro and Rio Grande do Norte coast (ANEEL, 2003).

The microclimatic conditions along the cliffs are prone to generate turbulence, which to be studied require specific measurements and estimates. Therefore it is necessary to understand the vertical profiles, speed, intensity and spectrum of the turbulence of the winds, in order to know the height of the recirculation bubble generated by cliffs and the turbulence in the interior. These aspects are of fundamental importance for the installation of more efficient wind power plants. Since this level of detail currently is not present in the Atlas of the Brazilian Wind Power Potential, detailed studies are required for the installation of wind turbines in such areas.

As the complex landforms influence the velocity profiles and the formation of turbulence, the Brazilian wind potential could be harnessed more efficiently by taking advantage of the favorable regime of the coastal winds, and possibly by utilizing the higher altitudes and relief complex of parts of the interior of the country, such as some areas of the state of Minas Gerais.

Simulations which take into account the wind recirculation zones created by the state's rugged terrain and the wind regime at higher altitudes may be decisive in viability studies to meet localized demands or to compose the National Interconnected System (SIN) in wind turbine installation.

2. BOUNDARY LAYER

The Earth's surface is at the lower limit of the atmospheric domain. Transport processes that occur between 100 and 3000 meters of altitude atmosphere changes this limit, creating what is called the Atmospheric Boundary Layer (ABL) (Garratt, 1992).

The ABL can be defined as the region of the atmosphere that is directly affected by the land surface properties (friction, heating and cooling), which generate turbulence until some point where there is a thermal inversion that limits air exchange (Garratt, 1992).

The ABL is directly affected by the topographic and orographic characteristics of the land. Its thickness varies depending on the time and space, and can reach kilometers and is related to temperature variations during the day. However, the soil radiation is mainly responsible for the formation of the ABL and on warmer days it generates more intense exchanges of energy, mass and momentum (Moreira, 2012).

The ABL consists of an inner region and an outer region. In the outer region, the flow shows a small dependence on the nature of the surface and in the atmosphere, the Coriolis force due to the earth rotation is also important. The flow in the inner layer (also called the wall or surface layer) is mainly dependent on the surface characteristics and is unaffected by rotation. The transition between the inner and outer layers is not abrupt, but is characterized by an overlapping region. The influence of the surface is directly felt on the interfacial sublayer, which is the air layer above the rough elements such as the surfaces of land or ocean (Pires, 2009).

Internal Boundary Layer (IBL) is formed at the bottom of the ABL and is an important meteorological consequence of air movements, through the changes in surface conditions. It is usually developed as a result of atmospheric flow response to a discontinuity in the surface, by a change in step, roughening (mechanical), temperature or humidity (thermal) (Garratt, 1992).

The growth of IBL height (δ_{IBL}) under conditions of neutral stability, without step topographic surface, follows a power law, as described in Eq. (1), of the type initially proposed by Elliot (1958):

$$\delta_{IBL} = ax^b \tag{1}$$

Where:
x is the distance from the discontinuity point (B);
a and b are constants that depend on the surface roughness.

The coefficient values (a) are between 0.35 and 0.75 and the coefficient (b) ranging from 0.1 (smooth surface) to 0.4 (urban areas). This is valid until 1 or 2 km from the coast, where δ_{IBL} becomes constant (Kallstrand and Smedman, 1997).

The value of the exponent α (dimensionless) depends on the atmospheric stability, wind speed, aerodynamic roughness and the range of heights. According to Arya (1988), this exponent achieves values of 0.10 for smooth surfaces such as sea, ice and snow and around 0.40 for well-developed urban area surface. Some studies have found α values of 0.15 (Blesmann, 1973), and 0.11 (Hsu et al., 1994; Loredo-Souza et al, 2004) on the ocean surface. On open fields this figure is around 0.17, according to Alvarez y Alvarez and Wittwer (2006). For rough surfaces, such as forests or areas with obstacles, α values are of the order of 0.31 (Hsu et al., 1994), 0.34 (Loredo-Souza et al., 2004) and 0.25 (Alvarez y Alvarez and Wittwer, 2006).

Pires (2009) defines δ_{IBL} as the height where the vertical derivative (z) of vorticity (ω) becomes substantially zero, which corresponds to a virtually constant profile, and speed varying almost linearly with the height, as in the case of the ABL above the IBL.

According to Moreira (2012), it is the inner boundary layer where all the disturbing effects occur due to changes in surface roughness.

Conditions such as surface roughness and shape of the field affect the air flow. Steep terrains create acceleration in flow velocity due to compression of the laminate layers, leading to higher speeds. In more extreme cases, when the laminating layers are very compressed, the fluid moves to the side of the obstacles, rather than go over the top. At the downstream side of the obstacle, the flow expands in the laminating layers, causing a deceleration of the flow, which reduces its speed. In soft hilly terrain it is reasonably safe to assume that the flow as a whole is decelerated. In the area studied here, the wind regime is very intense, regardless of time of day (Fisch, 1999). According to Loredo-Souza et al. (2004), for winds with hourly averages winds over 10 m/s, the flow is turbulent enough to eliminate the thermal effects and the atmosphere may be considered neutral. For this situation, the appropriate description of flow is usually accomplished by averaging instantaneous local velocity profiles. Several experimental conventions allow making the average wind speed adjustment.

An adequate description of the flow is usually accomplished by averaging instantaneous local velocity profiles. Several experimental convetions allow the adjustment of average wind speeds to be performed; in this case the Logarithmic Law and the Power Law were used.

It is observed that the profile behaves as a logarithmic function given by Eq. (2):

$$V = \frac{u*}{k}\left[\ln\frac{h}{z_0}\right] \tag{2}$$

Where:
V is the wind speed at the height h above the ground (m/s);
z_0 is the terrain roughness factor;
u^* is the friction velocity (m/s);
k is the Von Karman dimensionless constant, usually adopted as 0.4.

The estimate of z_0 is performed using data of the vertical wind profile and extrapolated to a time when the wind is zero. According to Arya (1988), z_0 on open and calm sea regions have values of the order of 10^{-4} m, for coastal regions it has values of the order of 10^{-3} m, in areas with lots of trees and a few buildings around its values are 0.1 to 0.3 m, and for areas of suburbs and low density urban centers the values are between 0.4 and 0.6 m. The same values were found in Hsu et al. (1994) for the categories of open sea and coastal areas. For smooth surfaces such as open ponds and fields, this parameter is presented in the order of 0.03 m in the work of Blessmann (1995) and Alvarez y Alvarez and Wittwer (2006). Considering high density urban land, the value of z_0 stood at around 0.3 m (Alvarez y Alvarez and Wittwer, 2006).

The friction velocity u^* is the shear stress of the boundary layer near the ground and can be described by Eq. (3):

$$u^* = \sqrt{\frac{\tau_s}{\rho}} \tag{3}$$

Where:
τ_s is the shear stress of the boundary layer near the ground (N/m²);
ρ is the density of air (kg/m³).

2.1 Governing equations

The governing equations of the flow are the mass conservation equations, the transport equations of momentum, and the air equation of state.

For this study, the energy equations were not considered, since temperature variation can be neglected due to high wind speed on 10 m above the surface at the location where the data was collected.

The altitude change of 1,000 meters above sea level causes a 9% decrease in the average energy density and decrease of temperature to 15° C causes an increase of about 2% in the average energy density (ANEEL, 2003).

3. METHODOLOGY

For the solution of the proposed problem the physical and numerical methods used in the implemented commercial software will be described. Due to the complexity of the phenomena involved in the simulation of the actual atmospheric flow, a simplified numerical model boundary layer (ABL) was used in this study to examine the flow in a more simple way, just considering mechanical parameters without the influence of thermal effects and with a constant surface roughness. The mesh parameters and turbulence models defined as most appropriate for this type of simulation are evaluated: the mathematical model, the computational domain and the numerical method to be used will be specified.

The studied area covers the northern coast of the state of Maranhão. This region has typical characteristics, with a smooth surface region (ocean) near a rough surface (mainland). The local topography resembles a step, since the continent is a relative topographical variation (cliff) with large slope and a height of approximately 50 m being the top of a relatively flat region.

The STAR-CCM+ commercial software from CD-Adapco will be used in this numerical study. This code is widely used commercially to present a range of models capable of dealing with various problems, having the following numerical characteristics: it uses the finite volume method for the solution of RANS transport equations; it shows the main turbulence models of Reynolds stresses; it uses wall functions for the treatment of the boundary layer on formulations for the viscous sublayer where turbulence models employ the specific rate of dissipation of turbulence; it has second order discretization schemes for the terms of equations in time and space; it solves coupled in co-located loops; it supports three-dimensional mesh with elements of tetrahedral, hexahedral and pyramidal prismatic forms. The results generated by the computer package were compared with numerical results obtained in an experimental wind tunnel and with published measured observational data obtained on site.

After entering data, which corresponds to the wind on the cliffs of the north coast of Maranhão, into the computer package it will be possible to compare the data available in the literature with data obtained by the STAR-CCM+, thus validating the profiles of wind speed in the region. Importantly, the northern coast of Maranhão was chosen because of the availability of wind data obtained in the towers of the Alcântara Launch Center as well as the availability of previous studies of ABL there.

3.1 Pre-processing

Pre-processing is the problem entry into the CFD software interface, the necessary activities include the following: defining the geometry, region of interest, meshing, selection of physical and chemical phenomena being modeled, defining the fluid properties, specifying the boundary conditions and the mesh tests.

The definition of physical boundaries is the representation of the geometry of the surfaces involved, the model developed in this work is the representation of a section of Alcântara's cliff which is fifty meters in height and with ninety degrees inclination relative to the ground.

In order to reduce the number of elements and reduce computational time, the model was designed on a scale of 100: 1, the control area is three meters in height and six meters long, containing a cliff with fifty meters height and two hundred meters of soil.

To simulate the ocean length and the length after the step, after several tests, it was concluded that the scale used was sufficient to develop the wind and the recirculation zone induced by the step.

According to Reuter 2004, the maximum height of the Oceanic Boundary Layer (OBL) in the Alcântara region is three hundred meters, which justifies the choice of the control area height.

The mesh most suitable for this simulation was the trimmed mesh, the domain contained three refined zones and there were twenty prism layers near the wall, as shown in the Fig. 1.

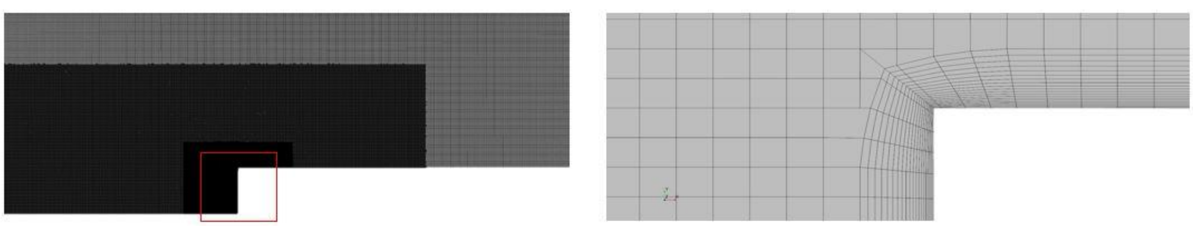

Figure 1. Mesh refinements and prism layers near the walls.

3.2 Post- processing

For data analysis and subsequent validation, plots were mounted using the "Scenes" software, which shows the mesh, the scalar representation and the vector representation of speed in color scales, making it possible to analyze the formation of the Internal Boundary Layer and flow behavior.

4. RESULTS

The RMS residual error tolerated for the final convergence was 10^{-4} for all simulations. The simulations were executed in a computer with a 12 Intel® Xeon® E5-1650 of 3.5 GHz processor with 32 GB RAM memory.

After all stages of implementation of the numerical model of the STAR-CCM + software, the simulation began initially as wind input conditions at constant speeds. In these preliminary simulations the initial turbulent flow condition was not formed along the ocean length, reaching the coastal cliff as a laminar flow; thus the generated boundary layer had much greater heights than those found in the experimental measurements.

The solution to force the development of the boundary layer and consequently the unification of the recirculation zone was to increase the number of the initial five hundred iterations to two thousand iterations, causing the result to converge and close significantly toward the results founds in the literature as shown in Fig. 2, for the velocity profile generated for a reference speed of 3m/s (Re = $1x10^7$).

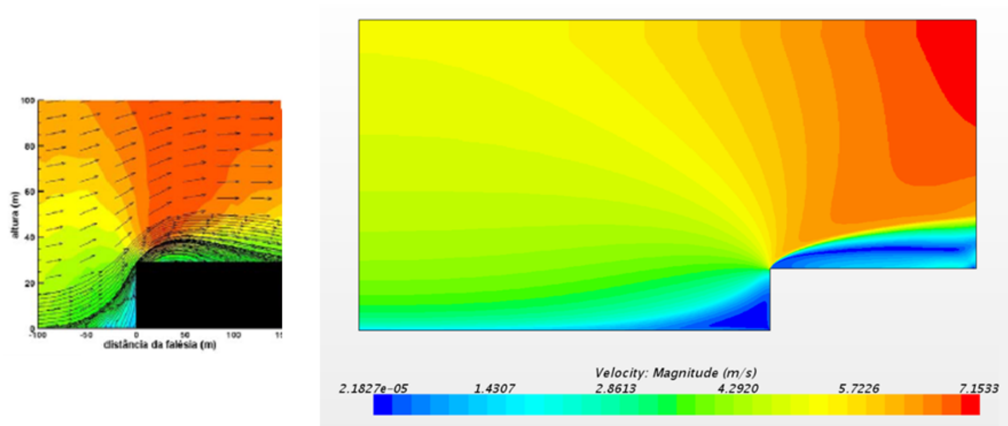

Figure 2.Comparison between expected and achieved results.

Three planes with different heights were constructed to evaluate the influence of the velocity profiles along the flow. The planes 1, 2 and 3 were constructed with respective heights 0.7m; 0.8m and 1m. It was found that by increasing the module of the input speed profile from 3m/s (Re=$1x10^7$) to 10m/s (Re=$3,3x10^7$), there was an increase in the velocity gradient between the planes constructed, as can be seen in Fig. 3.

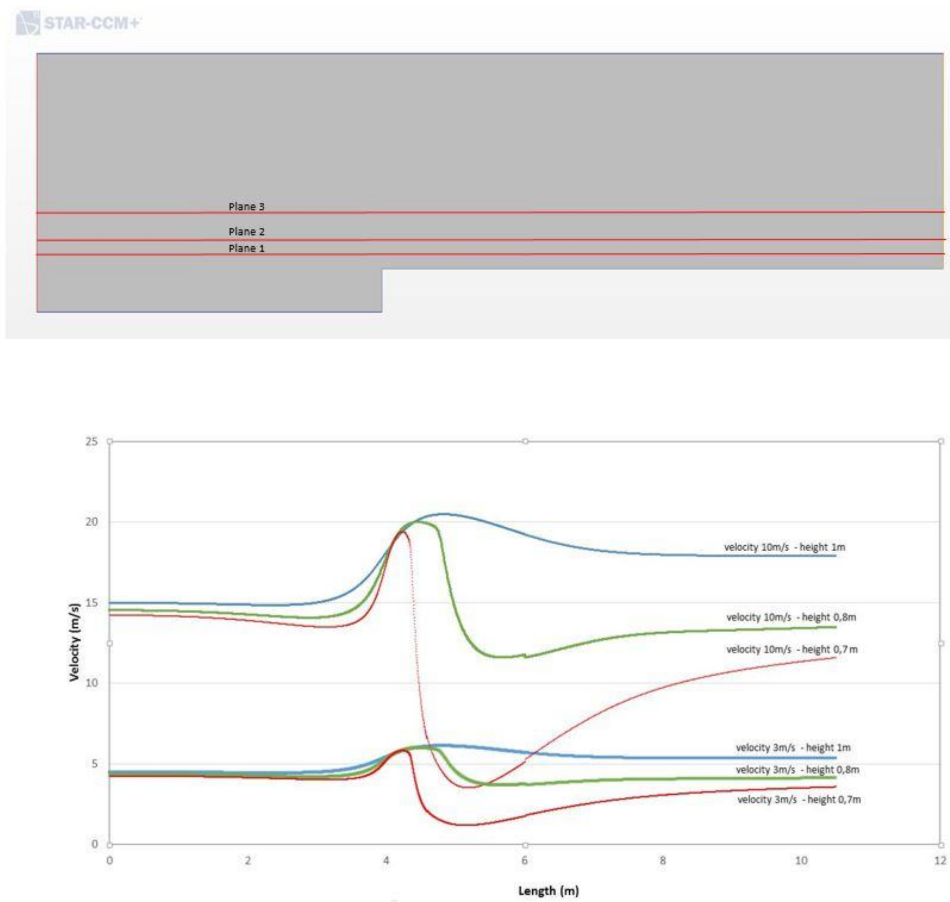

Figure 3. Flow velocity along the planes.

Although the initial study presents turbulence model k-ε as the most suitable since simulation comes from an external flow where interactions with the walls are less relevant than the average flow, the turbulence model k-ω SST which was viewed with great strength to solve the equations near the surfaces, properly representing the edge effects and has not lost the resolution to calculate the average flow, away from the wall, representing the phenomena that occur within the boundary layer.

5. CONCLUSION

Wind energy is a renewable energy source already used in many countries in the world that generates a reliable source of energy, inexpensive and clean. Such technology can and should be disseminated on a larger scale in Brazil, since we have already mapped several regions with excellent wind potential, such as the Northeast coast. The wind regimes in Brazil intensify in the months when the rainfall is less and the levels of the hydropower dams, the main source of national power, are at the lowest levels, thus promoting the establishment of wind farms as a complementary power source.

Along with the regime of favorable winds, different regions with rugged terrain exists in our country, such as the Alcântara area in the state of Maranhão, which has cliffs that create changes in wind speeds generating turbulence. Such turbulence takes place within a specific region bounded by the inner boundary layer.

The fluid dynamic model created in this work in order to simulate the velocity fields and wind direction to a well behaved atmospheric boundary layer is efficient to predict the wind speed and direction in steady state conditions with the Reynolds number less than 3.0×10^6.

The height of the internal boundary layers displayed in the current model are very close to the heights available in the literature obtained generated by other numerical programs, however this model has some restrictions that limit their use in unstable atmospheric boundary layer conditions. The main restrictions are imposed by computational limitations, the thermal and transient effects that were not considered in this work.

To serve as a basis for studies of optimal installations sites for new aero generators more efficient local study should be continued, implemented in the ocean and surface roughness models and in the 3D simulations, as it will be necessary to model the topography of the region in order to generate more reliable results.

In a next phase, thermal effects should be considered, which will allow the model to be used in different regions that have the irregular terrain, as is the case of Minas Gerais, and do not have a constant and virtually uniform ocean breeze as occurs in the Alcântara area.

6. ACKNOWLEDGMENTS

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