NUMERICAL SIMULATION OF NEUTRAL ATMOSPHERIC BOUNDARY LAYER FLOW

Gilberto Augusto Amado Moreira, gilbertomoreira@yahoo.com.br
Ramon Molina Valle, ramon@demec.ufmg.br
Wagner Luis Silva de Carvalho, wagnerlsc@yahoo.com.br
Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, Av. Antônio Carlos, 6627 – Pampulha – 31270-901 – Belo Horizonte, MG, Brasil.

Maurissone Ferreira Guimarães, mauris@cemig.com.br
CEMIG - Cia. Energética de Minas Gerais, Brazil Avenida Barbacena 1.200 - Santo Agostinho - 30161-970 – Belo Horizonte, MG, Brasil.

Abstract. *A numerical model is proposed in this paper to simulate the atmospheric boundary layer (ABL). The results obtained by the numerical model were validated using experimental data presented in the literature. The governing equations of the geophysical flows are the continuity, momentum and energy conservation equations. The momentum equations are coupled to the energy equation by an equation of state. Turbulence is considered in the model using RNG k-ε model. The irregularities of the terrain due to the vegetation are treated as an average roughness. The computational domain is defined as an area far enough from the interest region in order to guarantee the development of the wind flow from the inflow boundary edges. The top boundary of the domain is prescribed at least 500 m above the atmospheric boundary layer. At this altitude the wind flow is considered stable enough so that the Newman boundary condition can be applied. The results obtained can be used for further purposes, such as the determination of the swinging of cables isolation strings and to determine the ampacity of transmission cables. Experimental results from Askervein are used to validate the numerical model. Hence, numerical results are presented for a topography of Acuruí, in the state of Minas Gerais, Brazil.The numerical results showed good agreement with the experimental values of Askervein.*

Keywords: *Atmospheric Boundary Layer, Numerical Mode, CFX*

1. INTRODUCTION

The surface of the earth is at the lower limit of atmospheric field. Cases of transport that occur between 100 and 3000m of the atmosphere change this limit, creating what is called the atmospheric boundary layer (ABL). The rest of the troposphere is called the free atmosphere. The study of the flow on a real topology within the ABL always interested to meteorologists, engineers, environmentalists, military, sports, among others, for various reasons and applications, such as dispersion of pollutants, positioning of wind turbines and its destructive effects on structures due to the action of wind. The investigation of pollution has been highlighted daily in the general media. Apart from pollution, the prediction of the behaviour of the wind helps to design more efficient routes for transmissions lines (LTs), as the balance of chains of insulators, cooling of cables and other factors may interrupt or hinder the supply of energy and capacity of transmission of cables.

The modeling and simulation of the atmospheric boundary layer can be an important project tool. The validation of the model using experimental data will produce correlations between the topography and the wind pattern. Velocity and temperature profiles near the ground can be predicted for any region in which the topography is assumed to be known. It is important to remark the necessity to carry on computational studies concerning the changes in the local climate due to the results of the men action and its effects on the atmospheric boundary layer. The knowledge of such effects is an import feature in the project of LTs. In this work, a numerical study of the wind flow of a real terrain is presented. In the terrain are observed high slopes on its surfaces and presence of grass, forest and buildings as suburbia. The numerical solution of the model will provide velocity profiles near to the terrain's surface.

The computational domains should include a developing flow region surrounding the interest region, from the boundaries of the domain. According to "Albertson and Parlange (1999)", a typical domain for simulation of atmospheric flows should be higher than 6 km in x and y directions over the topology. The top boundary should be higher at least 500 m from the height of the atmospheric boundary layer. On this altitude, the wind flow is considered stable, so the Neumann boundary condition can be used for all flow variables. The ground boundary presents major influence on the turbulence structure compared to other boundaries. Also, this boundary provides the heat flux to the flow which are responsible by the convective air movement.

The models used for simulation of wind fields are classified in three classes: global circulation models, climate prediction models and mesoscales models, "Camilla et. al. (1999)". The global circulation models use domains between 200 and 500 km and they are used to analyze wind fields above earth surface. The climates prediction models use domains between 50 and 100 km and they are used to predict structures for climatic fronts, "Camilla e al. (1999)". The mesoscales models use typical domains between 2 and 50 km and they are used in the study and predict the velocity and temperature profiles of the wind on topologies. In that work, the results of simulation of the ABL allow a theoretical analysis of the distribution of the velocity of the wind in neighboring areas to a LT. The results were validated using experimental data of the literature and experimental field data, in order to ensure the accuracy and robustness of the numerical model. The proposed model can be applied to several geophysical problems as well as engineering problems. The model can solve variations of air density, resultants of the thermal effects and the altitude, through the Boussinesq's approach. The turbulence model used in this work for the study of the ABL is the RNG k-ε, thoroughly used in atmospheric flows, "Zhang et al. (1996)". The model proposed by ABL belongs to the class of mesoscales models and it does not consider the so-called Coriolis effect, which can be described as the effect of the earth rotation on the structures of the flow. This paper presents numerical results of the behaviour of atmospheric flow on real terrain in a region known worldwide, Askervein, and in a test region of Cemig, Acuruí-MG, to check the influence of this flow over transmission line

2. METHODOLOGY

2.1. Mathematical model

The methodology used is the same used in models of Mesoescalas, where the forces of Coriolis are neglected. The equations (1 and 2) represent respectively, conservation of mass and momentum, respectively, under the decomposition of Reynolds and Boussinesq approximation of where, u_i are the components of speed, is ρ_0 density of reference, is the p pressure, k is the kinetic energy, t is time and ν_t is the viscosity effective. The term I defined in Equation 2, represents the end of fluctuation.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial}{\partial x_i}\left(\frac{p}{\rho_0} + \frac{2}{3}k\right) + \frac{\partial}{\partial x_j}\left[\nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \underbrace{S_w}_{I} \tag{2}$$

The term of fluctuation features several models available in literature. Usually, the models made by Uchida, and "Uchida and Onya (1999)", "Huser et al. (1997)" and "Montavon (1998)" using the nearest Boussinesq and models of turbulence derived from the model RNG *k-ε*.

Where they have made the following considerations:

a) The dynamic viscosity (μ) and the thermal conductivity (k) are considered constant in the entire fluid domain;
b) The speed of the flow present magnitude on which the fluid can be considered incompressible;
c) The turbulence fluctuations are very low when compared with the respective mean magnitudes;
d) The thermal effect associated to the viscosity of the fluid can be disregarded, and,
e) The density fluctuations are significant only when multiplied by the vector of the gravity (g).

2.1.1 Turbulence Model

The model of turbulence quite robust and capable of predicting the geophysical flows is the model RNG k-ε, which uses the turbulent viscosity (μ_t), together with the equations of transport of the turbulent kinetic energy, k, and the dissipation of energy, ε, where these terms are defined by CFX (2004) as:

$$\frac{\partial(\rho k)}{\partial t} + \nabla\cdot(\rho U_k) = \nabla\cdot\left[\left(\mu + \frac{\mu_t}{\sigma_{kRNG}}\right)\nabla k\right] + P_k - \rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla\cdot(\rho U_\varepsilon) = \nabla\cdot\left[\left(\mu + \frac{\mu_t}{\sigma_{\varepsilon RNG}}\right)\nabla \varepsilon\right] + \frac{\varepsilon}{k}\left(C_{\varepsilon 1RNG}P_k - C_{\varepsilon 2RNG}\rho\varepsilon\right) \tag{4}$$

$$\mu_t = C_{\mu RNG}\,\rho\frac{k^2}{\varepsilon} \tag{5}$$

where:

$$C_{\varepsilon 1RNG} = 1,42 - f_\eta \tag{6}$$

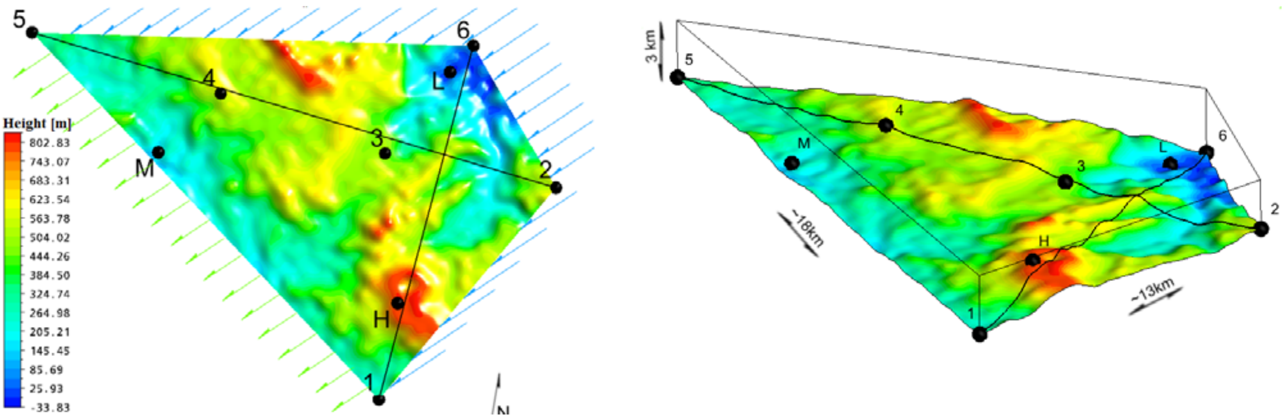
$$f_\eta = \frac{\eta\left(1 - \frac{\eta}{4,38}\right)}{\left(1 + \beta_{RNG}\eta^3\right)} \tag{7}$$

$$\eta = \sqrt{\frac{P_k}{\rho C_{\mu RNG}\varepsilon}} \tag{8}$$

And $C_{\mu RNG} = 0{,}085, C_{\varepsilon 1RNG} = 1{,}42 - f_n, C_{\varepsilon 2RNG} = 1{,}68, \sigma_{kRNG} = 0{,}7179$ *and* $\sigma_{\varepsilon RNG} = 0{,}7179$ are parameters of the model RNG k-ε.

2.1.2. Computational domain and boundary conditions

The Figure 1(a) shows the domain of the area of Acuruí digitalized in CFX, showing 4 border points (points 1, 2,5 and 6), where the boundary conditions are known, and 2 internal points, are also measured (experimental data points 3 and 4). Furthermore, the points L, M and H, located at different altitudes, are used to examine the influence of relief in the profile of local speed of wind. The lines drawn between points 1, 6 and 2 and 5 represent approximately lines of transmission to 10 meters high seen from above, during which will be studied the effects of the roughness of the terrain in the speed of wind.



(a) (b)

Figure 1 - Domain computational of Acuruí with the points of experimental measurement

The conditions of contour used are presented in Table 1

TABLE 1 – Boundary conditions

Contorno	u	v	w	k	ε
In	$u(z)_{in} = u_{ref} \cdot \dfrac{\ln\left(z/z_0\right)}{\ln\left(z_{ref}/z_0\right)} [m/s]$	$v = 0$	$w = 0$	$k = \dfrac{u_*^2}{\sqrt{C_\mu}}$	$\varepsilon = \dfrac{u_*^3}{\kappa z}$
Out	$\dfrac{\partial u}{\partial x} = 0$	$\dfrac{\partial v}{\partial x} = 0$	$\dfrac{\partial w}{\partial x} = 0$	$\dfrac{\partial k}{\partial x} = 0$	$\dfrac{\partial \varepsilon}{\partial x} = 0$
Sky	$u = u_\infty$	$\dfrac{\partial v}{\partial z} = 0$	$\dfrac{\partial w}{\partial z} = 0$	$\dfrac{\partial k}{\partial z} = 0$	$\dfrac{\partial \varepsilon}{\partial z} = 0$
Wall	Surface not slippery (u = 0) and with average rugosity z_0, coupled with the function of wall.			$\dfrac{\partial k}{\partial y} = 0$	$\varepsilon = \dfrac{k^{3/2}}{l_p}$

where $u(z)_{in}$ in speed is given by logarithmic profile changed, u_{ref} the reference speed is achieved at a height of 10m, to which region of Askervein u_{ref} = 8.5 m / s [10] and u_{ref} = 5.0 m / s (Tower 5) for region of Acuruí-MG, u_* is the speed of friction, κ is the constant of von Karman (κ = 0.41), z_{ref} is the height of reference (10 m) and z_0 is the length of aerodynamic roughness. The literature recommends use for roughness, the following: z_0 = 1.00 m (city), z_0 = 0.30 m (forest), z_0 = 0.03 m (low gram) and z_0 = 0.0001 m (water).

2.1.3. Source Term

The boundary condition study is necessary to verify the influence of the source term, which is given “CFX (2004)”.

$$S = g \cdot \Delta\rho = g \cdot (\rho - \rho_0) \tag{9}$$

where S is term source, g is the acceleration of gravity, ρ is the density of the environment and ρ_0 (ρ_0 =1,185 kg/m^3) is the density of reference. According "Trifonopoulos et. al.(1992)", when considering the density gradient constant during the simulation, the number of Froude could be linked as follows:

$$F_r = U_\infty \Big/ \sqrt{g \cdot L \cdot \frac{\Delta\rho}{\rho_0}} \tag{10}$$

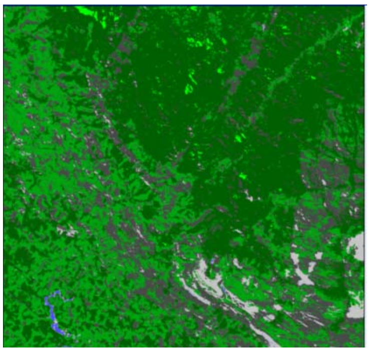
Where U_∞ represents the developed speed above 500 meters, $\Delta\rho$ the density variation between the base of the hill and its top, L (L = 116 m).the height of the hill and g is a acceleration of gravity. Thus, the term source in relation to the direction w (height) can be written as follows "Valle et. al. (2005)":

$$S_w = -\left(U_\infty^{\ 2} \cdot \rho_0 \big/ L \cdot Fr^2\right) \tag{11}$$

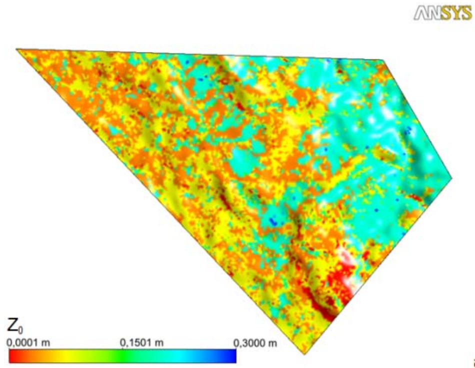
In order to validate the model for real topologies it is necessary an experimental data set containing the Froude number range.

2.1.4 – Roughness model

In Askervein the roughness was used constantly. However in Acurui, the coverage of real roughness of the land is taken through the shades of color photos of satellite, giving a characteristic to each surface of the ground. Thus it imposed a condition that the land contour, given by different colors that represent the values of roughness in meters. Figura 2 (a) map shows the roughness of the topography studied, through a satellite photo, indicating areas with water, forest, rocks, grass, etc. Already in Figure 1 (b) shows how the condition was imposed in the region contour of the ground by CFX.



(a)



(b)

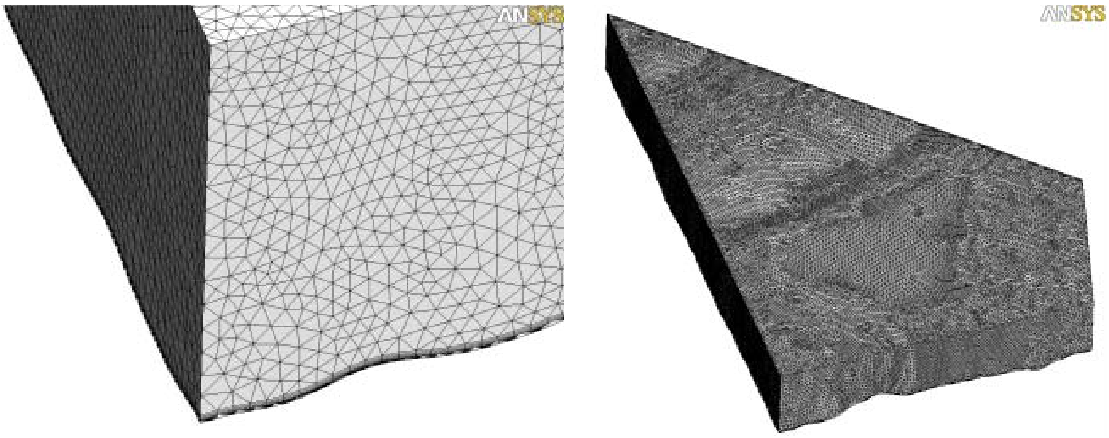
Figure 2 - Map of real roughness obtained for Acuruí-MG. (a) Picture extracted from the image satellite and (b) contour on the condition of Ansys CFX ® 11.0.

2.2 – Numerical model

The modeling and the simulation of the flow are made using the commercial package Ansys CFX-11.0, "CFX (2004)". This software possesses the following characteristics: discretize the conservation equations by the finite volumes method centered in the vertex; solves laminar and turbulent three-dimensional problems; uses unstructured and hybrid meshes; solves conjugated problems of heat and fluids flow. The use of no-structured meshes allows mesh refinements to be applied near the surfaces, where great variations of speed and temperature occur.

2.2.1 Mesh

The Figure 3 shows the three dimensional mesh of the complete domain. To generate this mesh it was necessary 1.597.189 nodes, resulting in 8.691.617 elements.



(a) (b)

Figure 4 - The three-dimensional mesh used

3. NUMERICAL MODEL VALIDATION

The validation presented in this work compares the obtained data of the model here shown with experimental data of the Askervein hill presented for "Taylor and Teunissen (1983, 1985, and 1987)". Askervein is a hill with 116 m high located at west coast of South Uist in Scotland. It is relatively isolated and smooth, with the apex at 126 m high above the sea level and its form is approximately elliptic, with the larger axis approximately 2 km of length, oriented in the direction 133º-313º (southeast-northwest - line B-B). The smaller axis, of 1km of length, is guided towards 43º-223º (Southwest-northeast - line A-A or AA-AA). Its vegetation is low and with non uniform rugosity. The field measures were made using several devices, measuring along the lines A-A, AA-AA and B-B, at 10m height above the surface of the hill, as showed in Figure 5.

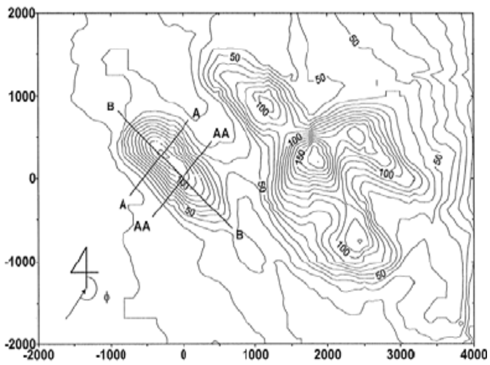
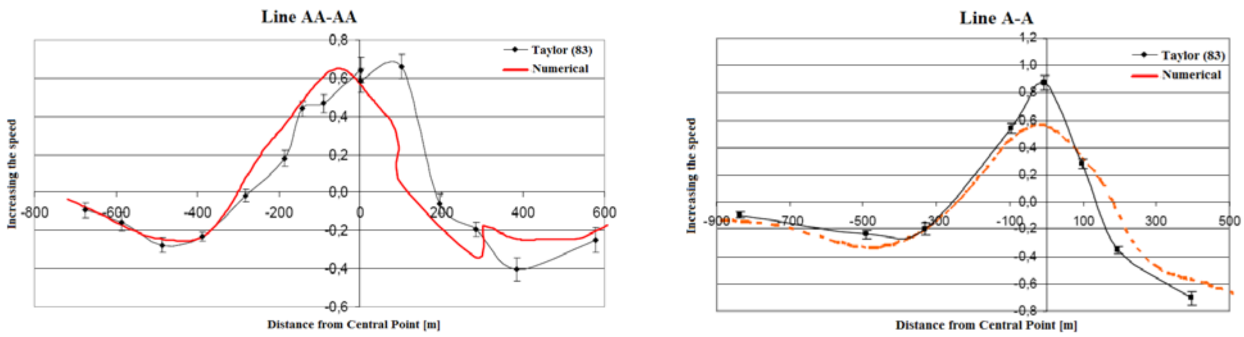


Figure 5 - Topographical Map of the Askervein hill. Sections of the measurements

In "Figure 6 (a) and (b)" the comparisons of the measured experimental results are presented for "Taylor and Teunissen (1983)" with the numerical results obtained of the present model along the lines A-A and AA-AA, respectively. These experimental results were obtained, according to the authors, for a neutral atmosphere, that is, for the Froude´s numbers larger than 1000. The relative increase velocity, shown in the "Figures. 3 (a) and (b)" represents how many times the local velocity is greater than the reference speed.



(a) (a)

Figure 6 - Validation of the numerical model. (a) along the line AA-AA (b) along the line AA-AA

The results presented in Figures (3a) and (3b) show that, even with a very refined mesh, the results of the model present a considerable difference when compared to the experimental data. On the other hand, the behavior of the two curves is similar, showing that the model behaves qualitatively similar to the experimental data. A revision of the literature has showed that practically all of the authors that validated their models with these same experimental data of Askervein had problems with the approach of experimental data

4. – RESULTS

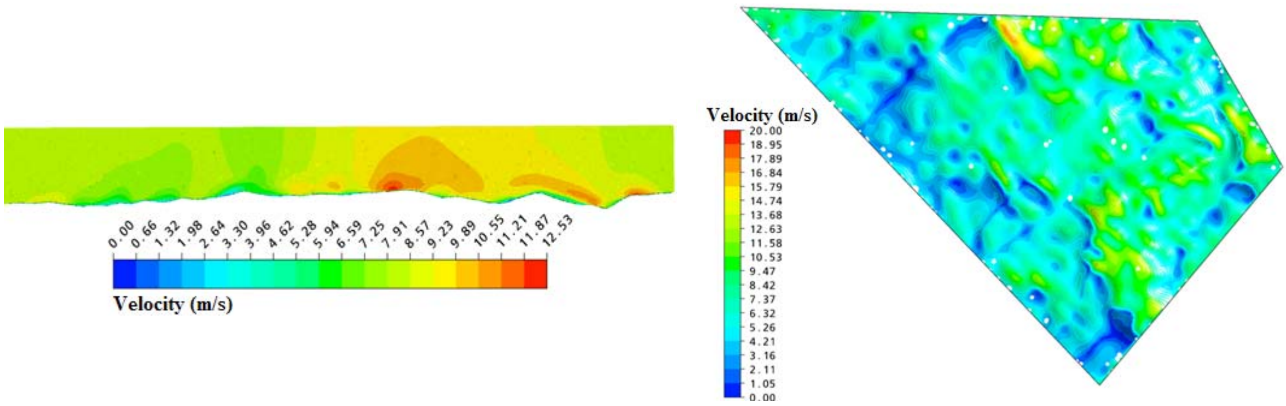
The validated model allows obtaining more reliable results for any land topography, whenever the necessary care is taken with the treatment of the boundary conditions, treatment of the source terms and cares with the used mesh. The presented results refer to the topographical map of the area of Acuruí, Minas Gerais, Brazil.

The results presented in this item considered a northeast flow of intensity of 5 m / s 10 meters high, with the representation of the vegetation and surface of Acuruí-MG, extracted by surface recognition software from satellite photos. This way an accurate roughness of the terrain can be obtained, thus resulting in a more realistic model.

Through the shades of color in satellite photos of the actual coverage of the roughness of the land is taken through a programme, giving a characteristic to each surface of the ground. The Figure 1 (b) shows the roughness of the land obtained for the region-testing Acuruí, represented by a range of colors representing the intensity of roughness for the types of coverage. It appears that the vegetation in this region ranging from water to forests closed, and used an average height of roughness for each vegetation, which is a very mathematical approach used in numerical simulations involving fluid – surface interaction.

The results presented for Acuruí-MG were analyzed on a plane on the line 6-1, fields of speed for a plane to 10 meters high, components of speed on the line 2-5 and 6-1 and finally, profiles of speed on all the items shown.

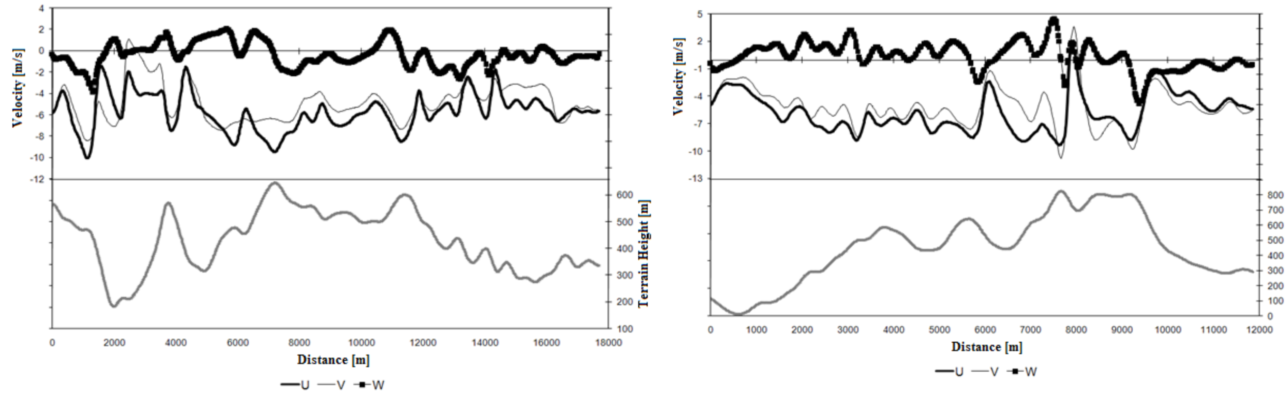
The Figure 7 (a) shows the speed found for the vertical plane along the line 6-1, obtained with this new roughness of the terrain. Proving the ability of the model to reproduce higher accelerations in the regions resulting from compression of the upper layers of the atmosphere. Already in Figure 7 (b) shows speed at 10 meters high for the entire field, obtained with the real roughness of the terrain.



(a) (b)

Figure 7 –Speed in a vertical line of 1-6 (a) and (b) 10 meters high for the entire field with the real roughness.

The Figures 8 (a) and (b) show the components of speed u, v and w on the line 2-5 and 1-6. Note on the figures that the contribution of vertical flow, represented by component w, is practically non-existent, since the model is not yet able to predict completely this component. The vertical component appears only near and on hills and valleys, where the flow suffers vertical acceleration and deceleration up and down those obstacles.



(a) (b)

Figure 8 – The speed components u, v and w on the line 2-5 (a) and 1-6.

The Figure 9 shows the profiles of speeds in point 3, 4, L, M and H for real roughness of the terrain, considering the speed and direction of the wind constant.

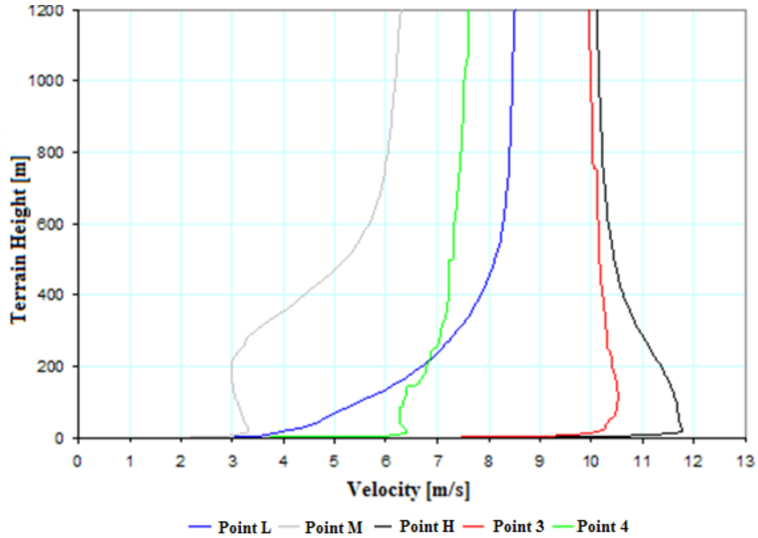
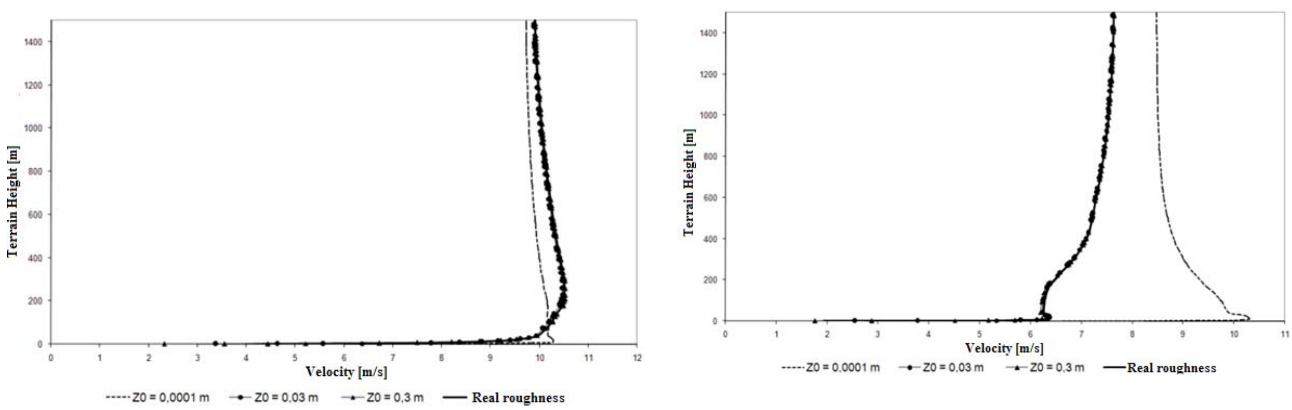


Figure 7 - Profiles of speed in points 3, 4, L (low altitude), M (recirculation point) and H (high altitude) with the real roughness.

The Figures 8 (a) and (b) show the profiles of speed in points 3 and 4, respectively, for different roughness studied.



(a) (b)

Figure 8 - Profiles of speed in point 3 (a) and 4 (b) for the different roughness studied

It is shown in Figure 8 that the roughness of the land has low influence on the velocity profile for different values of z_0. This can be explained by the location of the points discussed, which are located in a very uneven terrain. Thus, the very uneven topography of the land represents a level of roughness of greater scale than the vegetation itself. Thus, a point must be considered in a region of regular topography (flat terrain) to see if this hypothesis is true.

5. CONCLUSIONS

- A numerical model was developed for the study of the layer to limit atmospheric with the purpose of obtaining the correlation of the wind's profile;
- A validation of the model was proposed, through the experimental data of Askervein, in way to supply the necessary reliability for application of these theoretical results in overhead transmission line design of CEMIG
- The proposed model of atmospheric boundary layer can be applied a diversity of geophysical problems and of engineering, being capable to solve variations of density of the air, resultants of the thermal effects and of altitude;
- The used numerical model is capable to reproduce experimental values of fields of wind Velocity relatively with uncertainties low for several characteristics of the ABL;
- The uncertainty of the results is basically linked to the correct implementation of the boundary conditions and to the refine of mesh, resulting in high computational cost. In that way, a great obstacle to be overcome in the studies and simulations of the ABL is the obtaining of viable correlations among the implicit variables of the problem to try to simplify equations and to reduce the associated computational cost;
- Nowadays, the processing of the ABL in UFMG is being accomplished in a cluster with 400GFlops so the simulated cases process with several hours, what restricts the simulations a lot.

6. REFERENCES

Albertson, J.D. and Parlange, M.B., 1999, "Natural Integration of Scalar Fluxes from Complex Terrain", Advances in Water Resources, vol. 23, p. 239-252.

Camilla, G., Griff, J., Michel, O., and Vincent, D., 1999, "Transport and Mixing in the Atmospheric Boundary Layer", Lecture Notes, Aosta Summer School.

CFX (2004). "CFX-10 Solver and Solver Manager Guide", AEA Technology Engineering Software Ltd, UK.

Huser, A., Nilsen, P.J., and Skatun, H., 1997, "Aplication of k-□ model to the stable ABL: pollution in complex terrain", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 67-68, pp. 425-436

Montavon, C., Validation of a non-hydrostatic numerical model to simulate stratified wind fields over complex topography, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 74-76, 1998, pp. 273-282., 1998.

Taylor P.A. and Teunissen, H.W., 1983, "Askervein 82: an initial report on the September/October 1982 experiment to study boundary layer flow over Askervein", South Uist, Scotland. In: Internal Report MSRB-83-8. Downsview. Ontario, Canada.

Taylor P.A. and Teunissen, H.W., 1985, "The Askervein Hill Project: Report on the September/October 1983 main field experiment". In: Internal Report MSRB-84-6. Downsview. Ontario, Canada.

Taylor P.A. and Teunissen, H.W., 1987, "The Askervein Hill Project: Overview and Background data. Boundary Layer Meteorology", v.39. pp,15-39.

Trifonopoulos, D. A. e Bergeles, G. C. (1992) "Stable stratification effects on the flow past surface obstructions: A numerical study." Int. J. Heat and Fluid Flow, Vol. 13, Nº 2. pp.151 - 159.

Uchida, T. and Onya, Y, 1999, "Numerical Simulation of Atmospheric Flow Over Complex Terrain", Journal of Wind Engineering and Industrial Aerodynamics, vol. 81, p. 283-293.

Valle, R. M. ; Nascimento, C. A. M. ; Martins, M. A. ; Abreu, J. A. ; Moreira, G. A. A. (2005). "Numerical Mode l Validation of a Atmospheric Boundary Layer Over Complex Terrain." In: 18th International Congress of Mechanical Engineering, 2005, Ouro Preto, MG. Proceedings of the 18th International Congress of Mechanical Engineering. v. 1.

Zhang, Y.Q., Arya, S.P., and Snyder, W.H., A comparison of numerical and physical modeling of stable atmospheric flow and dispersion around a cubical building, Atmospheric Environment, vol. 30, n. 8, pp. 1327-1345, 1996.

5. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.