NUMERICAL MODEL VALIDATION OF ATMOSPHERIC BOUNDARY LAYER OVER COMPLEX TERRAIN

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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 k-ε model. The irregularities of the terrain due to the vegetation are treated as an average rugosity. The computational domain is defined as an area far enough 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 terrain boundary has a major contribution on the flow structure than the other boundaries. Therefore, more solution points are required to predict such flow variation, given by an unstructured tetrahedral mesh refined near the terrain surface. The relevance of this boundary is due to the fact of the mechanical production of the turbulence that exists because of the action of dragging forces on the surface and, still, for the heat flows responsible for the convective movements be originated from the surface. Since the numerical model for the atmospheric boundary layer has been validated using experimental data, it will allow reproducing the wind flow over a given terrain and identifying if the transmission line is really submitted to excessive mechanical tension. 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. The results presented in this paper consist on the reference data of wind speed from Askervein topology, whose experimental results are used to validate the numerical model. Hence, results are presented for a topography of Acuruí, in the state of Minas Gerais, Brazil.*

Keywords: Atmospheric boundary Layer, Numerical Model, Complex Terrain

1 – Introduction

The occurrence of four serious damages in transmission lines (LT) belong to Centrais Elétricas de Minas Gerais (CEMIG) in the last two years was caused by the wind. So, a research concerning the study of local behavior of wind flow in the some regions of the state of Minas Gerais, Brazil, was motivated by CEMIG. By means a wind field predicted by a previously validated computational method, it is possible to compare if the mechanical projects of LT are in agreement to the environmental and climate conditions. This condition includes not only the wind magnitude but also its periodic variation.

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 equations of the model will be produce velocity profiles close the terrain.

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 *e 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.

2 – Methodology

2.1 – Mathematical model

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

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial}{\partial x_i}\left(\frac{p}{\rho_0} + \frac{2}{3}k\right) + \frac{\partial}{\partial x_j}\left[\nu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \underbrace{\frac{\delta\rho}{\rho_0} g\delta_{i3}}_{I} \tag{2}$$

$$\frac{\delta\rho}{\rho_0} = -\frac{\delta T}{T_0} \tag{3}$$

$$c_p\left(\frac{\partial T}{\partial t} + u_j \frac{\partial T}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\mathrm{Pr}_T}\frac{\partial T}{\partial x_j}\right) + Q \tag{4}$$

Equations (1), (2) and (4) represent the conservation of the mass, momentum and energy, respectively, where, u_i are the components of speed, ρ_0 stands for reference density, p stands for pressure, k is the kinetic energy, g is the gravity acceleration, t is the time, ν_t is the effective viscosity, c_p is the thermal capacity of the air at constant pressure, Pr_T is the turbulent Prandt number, T is the temperature and Q is the rate of energy generation. Equation (3), known as state equation that allows to couple the equations of momentum, Equation (2), together with equation of the energy, Eq. (4). The term I, defined in Eq (2), it is known as fluctuation term. The definition of the fluctuation term characterizes several models available in the literature. Usually, the models presented in the literature: “Andreas, E.L. (1996)”, “Huser et al. (1997)”, “Kim, et al.(1998)”, “Montavon, C. (1998)” and “Uchida and Onya (1999)” use the Boussinesq’s approach and the turbulence models derived of the model k-ε, where they are made the following considerations:

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

2.2 – Models for the fluctuation term

The Uchida and Ohya´s model (1999), used in this work, defines the fluctuation term considering transportation of the density disturbance (ρ'), including the hydrostatic variation of the density ρ_B (z). The transport equation for the density disturbance is defined by the authors through equation:

$$\frac{\partial \rho'}{\partial t} + u_j \frac{\partial \rho'}{\partial x_j} = \alpha \frac{\partial^2 \rho'}{\partial x_j \partial x_j} - w\frac{d\rho_B}{dz} \tag{5}$$

Where α is the molecular diffusivity for the density. The disturbance of the density and the fluctuation term are defined as:

$$\rho' = \rho - \rho_B(z) \tag{6}$$

$$S_i = -\rho' \rho_0 g \tag{7}$$

Where ρ_0 is the reference density and w is the vertical component of speed.

The software CFX that allows the implementation of partial differential equation and additional equations as for example the state equation solves equations (1) to (5) numerically. Equation of the energy can be still coupled to this model because the variations of temperature in function of altitude promote alterations in the fluid density.

The transport scalar equation is a convection-diffusion equation with the source term defined as:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (u_j \phi) - \nabla \cdot \left(\left(\rho D_\phi + \frac{\mu_t}{Sc_t} \right) \frac{1}{\rho} \nabla \phi \right) = S_\phi \tag{8}$$

Where ϕ is the volumetric variable, D is the cinematic diffusivity (m^2/s), μ_t is the turbulent viscosity, Sc_t is the turbulent Schmidt number and S is the source term.

The usual model of turbulence in geophysical flows is the k-ε model, on which the turbulent viscosity (μ_t) is used together with equations of the turbulent kinetic energy, k, and the dissipation of this energy, ε. The turbulent kinetic energy and energy dissipation are defined as:

$$\frac{D(\rho k)}{Dt} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \Pi + G - \rho\varepsilon \tag{9}$$

$$\frac{D(\rho \varepsilon)}{Dt} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + C_1 \frac{\varepsilon}{k}\left[\Pi + G(1 - C_3)\right] - C_2 \rho \frac{\varepsilon^2}{k} \tag{10}$$

where μ_t is the turbulent viscosity defined as $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, Π is the term of kinetic energy (k) production and G is the fluctuation term, defined as:

$$\Pi = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_j}{\partial x_i} \tag{11}$$

$$G = g_i \frac{\mu_t}{\sigma_{t,\Theta} T_0} \frac{\partial \Theta}{\partial x_i} \tag{12}$$

The parameters of the model (C and σ) are defined in the Table 1.

Table 1 – Parameters of the Model k-ε

C_μ	C_1	C_2	σ_k	σ_ε	$\sigma_{t,\Theta}$	$\sigma_{t,C}$
0.09	1.44	1.92	1.0	1.3	0.9	0.9

2.3 – Boundary conditions

2.3.1 – Treatment of the inlet boundary conditions - Mathematical representation of the surfaces rugosity.

The inlet speed profile used in the literature is vertically logarithmic, uniform in the horizontal direction, given by Eq. (13) and (14):

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0} \right) \tag{13}$$

where:

u_* Friction speed

κ Von Karman´s constat ($\kappa = 0.41$)

As the friction speed is difficult to determine and does not have a physical meaning of easy understanding, it can be obtained a similar expression in function of a reference speed, measured directly in field to a reference of 10 meters height. This height is used as reference in all of the works of the literature and it was used for the installation of the systems of the speed wind measurement in our project.

This way, considering the friction speed, given from equation (13), comes the following:

$$u = u_{ref} \cdot \frac{\ln\left(z / z_0 \right)}{\ln\left(z_{ref} / z_0 \right)} \text{ [m/s]} \qquad (14)$$

where u_{ref} is the reference speed, measured to10m height (literature values = 8.8 or 8.2 m/s), z_{ref} is the reference height (10 m) and z_0 is the rugosity (literature values = 1.00m for town, 0.30 m for forest, 0.03m for low gram and 0.0001m for water).

The inlet profiles for the turbulent kinetic energy (k) fields and dissipation rate of the turbulent kinetic energy (ε) are also prescribed. Prescribing these profiles in the inlet plan of the computational domain, the wind speed and the class of atmospheric stability can be imposed. In the adopted model, the surface rugosity, the heat flow in the ground and the class of stability are the parameters that define atmospheric state, being these parameters defined as boundary conditions. The inlet profiles for k and ε they are also prescribed.

2.3.2 – Wall boundary condition

The wall condition (wall boundary condition) is applied automatically by CFX in the domain surface (land). The land is considered as a surface not slippery (u = 0) and with average rugosity z_0. In relation to the energy transportation the surface can be considered adiabatic, with prescribed flow or isothermal. In this case the isothermal condition at 25 ^{o}C was adopted.

2.3.3 – Symmetry boundary condition

The symmetry boundary condition adopted for the top and for the lateral domain. These boundary conditions guarantee null flow of all greatness in the respective surfaces.

2.3.4 – Outlet boundary condition

The outlet boundary condition domain was imposed through the specification of the average of the null static pressure and null gradient towards the direction of flow for the other conditions.

2.4 – The Froude number

The boundary condition study is necessary to verify the influence of the source term, which is given:

$$S = g \cdot \Delta\rho = g \cdot (\rho - \rho_0) \qquad (15)$$

Where S is the source term, g is the gravity acceleration, ρ the density and ρ_0 the reference density. The source term can be related with the Froude number (Fr), defined as:

$$Fr = \frac{V}{\sqrt{gL}}$$

Where V is the velocity and L is the characteristic length. The Froude number can be defined as:

$$Fr = \frac{U_\infty}{(g \cdot L \cdot \Delta\rho / \rho_0)^{1/2}} \qquad (16)$$

where U∞ represents the speed developed above 500 meters and the Froude number expresses the relationship between the inertia forces and the gravity forces. Therefore the source term in relation to the direction w (height) can be written in the following way:

$$S_w = -\frac{U_\infty^{\ 2} \cdot \rho_0}{L \cdot Fr^2} \qquad (17)$$

Where ρ_0 is the reference density (1.185 kg/m^3) and L is the characteristic length (L = 116m). This way, to validate the model with topographical maps of the literature becomes necessary to define the band Froude number on which the literature presents experimental data, as showed in the table 3

Table 3 - Correlation between the Froude number and Atmosphere State

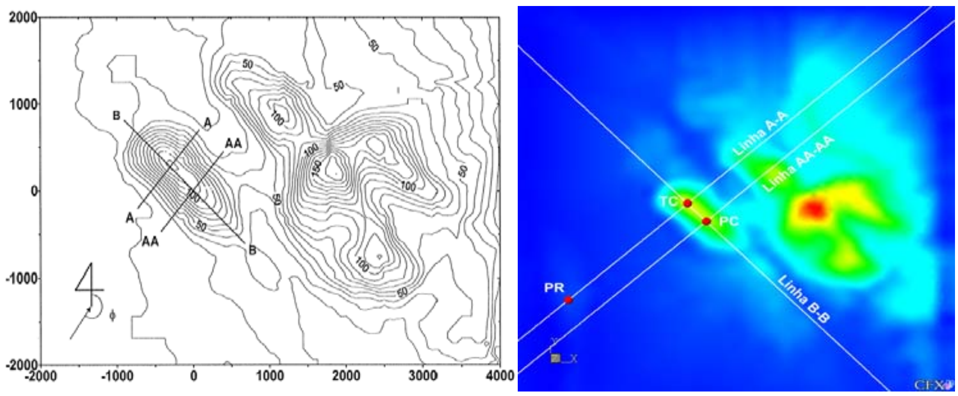
Froude Values	Atmospheric State
Above 1000	Neutral
10 - 1000	Stratified and Stable
-100 - 10	Unstable

2.5 – Numerical treatment equations

The modeling and the simulation of the flow are made using the commercial package CFX-5.6, "CFX-5.5 Documentation (2002)". 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 non-structured 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.

3 – Model validation

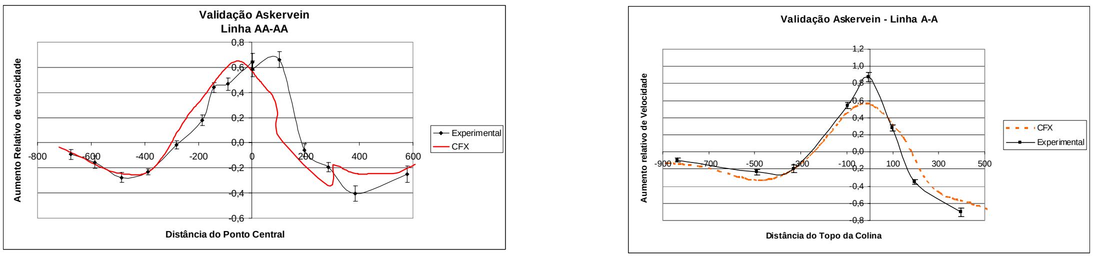
The validation presented in this work compares the obtained data of the model here shown with experimental data of the Askervein hill presented for "Taylor and Teunissen (1983, 1985, and 1987)". Askervein is a hill with 116 m high located at west coast of South Uist in Scotland. It is relatively isolated 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 "Fig. 1".



(a) (b)

Figure 1 - Topographical Map of the Askervein hill. (a) Sections of the measurements (b) digitalized map in CFX

In "Figure 2 (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 "Figs. 2 (a) and (b)" represents how many times the local velocity is greater than the reference speed.



(a) (b)

Figure 2 - Validation of the numerical model. (a) along the line AA-AA (b) along the line AA-AA

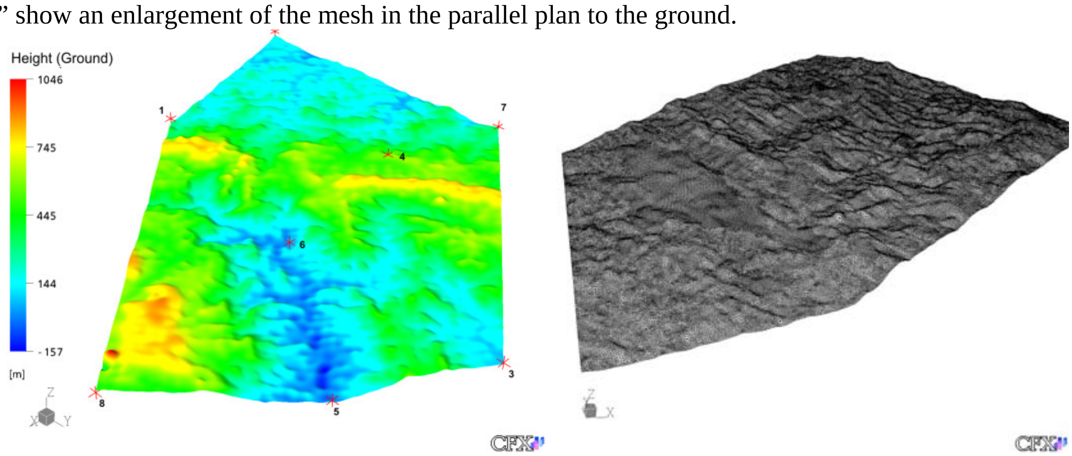
The results presented in Fig. (2a) and (2b) show that, even with a very refined mesh, the results of the model present a considerable difference when compared to the experimental data. On the other hand, the behavior of the two curves is similar, showing that the model behaves qualitatively similar to 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 maps of the areas of Acuruí and Belo Horizonte areas, Minas Gerais, Brazil.

4.1 – Numerical results for Acuruí topographical map

"Figure 3(a)" shows the domain of the area of Acuruí digitalized in CFX, showing 6 border points (points 1, 2, 3, 5, 7 and 8), where the boundary conditions are known, and 2 internal points, where can are also measured with experimental data (points 4 and 6). "Figure 3(b)" shows the three-dimensional mesh of the complete domain. To generate this mesh they it was necessary 820.000 nodes, that are equal to 3.500.000 elements, occupying 2Gbytes of memory. Each simulation is needed approximately 20 hours of processing in a IBM with 2 processors of 3,06 GHz. "Figure 4" show an enlargement of the mesh in the parallel plan to the ground.



(a) (b)

Figure 3 - Domain of Acuruí (the) with the points of experimental measurement (b) with the three-dimensional mesh

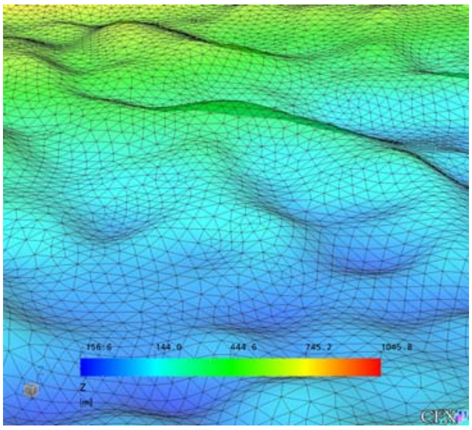
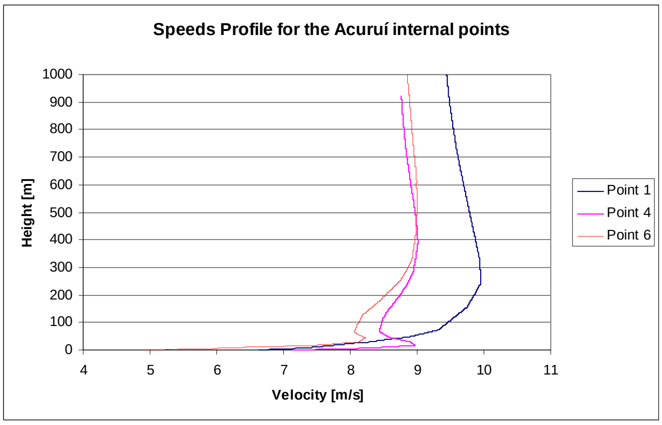


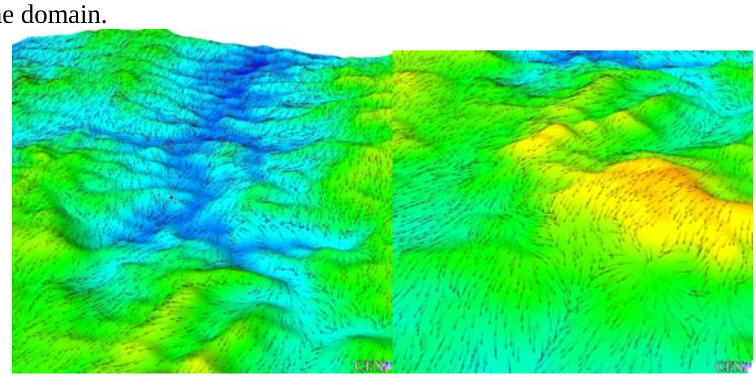
Figure 4 - Details of the mesh in the surface of the ground for the area of Acuruí.

"Figure 5" shows the speed profiles for the points 1, 4 and 6 of the Acuruí-MG area. It is noticed that in the point 1, due to its lower and plane surface, the Speed profile does not present large acceleration of the speed, remaining a more parabolic profile. The internal points 4 and 6, shows that accelerations appear for heights between 30 and 40 meters. These speed profiles were obtained for boundary conditions regarding the average values of speed and predominant direction of measured winds at border points of 10 m of height of the ground, of positions shown in the domain of Fig. 3(a).



Fgure 5 – Speed Profile for the Acuruí internal points 1, 4 and 6

In "Figures 6(a) and 6(b)" enlargements of the ground are shown, with the vectors of speed to a height of 10m above the ground. "Figure (6a)" represents the flow through a valley, where is observed that there is a tendency of the flow to follow the valley and to remove of the elevations, in some certain moments still possible to invert the course of the flow. "Figure 6(b)" shows the flow in some points of the domain, where there are a lot of irregularities on the land and elevations to generate accelerations of the flow, getting the speed of 17 m/s, showing that the fastest speed happens in the highest areas of the domain.

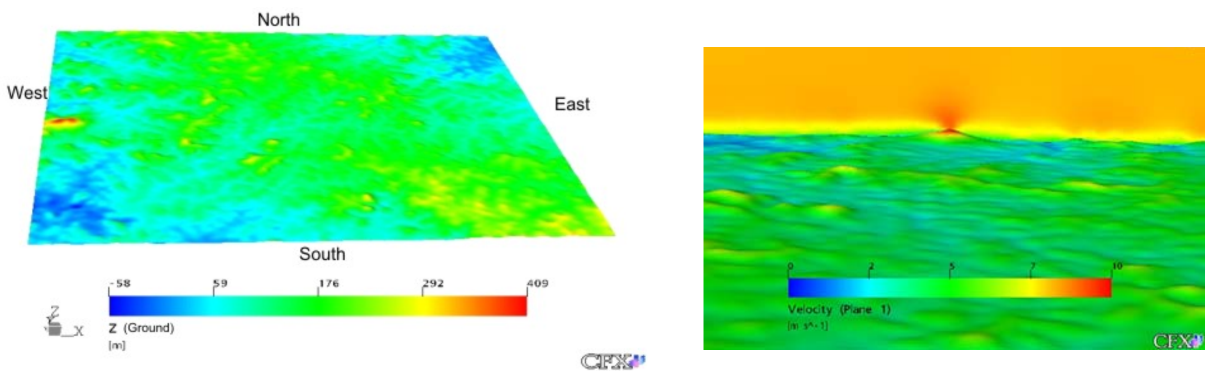


(a) (b)

Figure 6 - Vectors of speed for an enlarged Acuruí area (a) in internal points of valley (b) in internal points of high elevations

4.2 – Numerical results for the Belo Horizonte topographical map

Compared with Acuruí, the Belo Horizonte area is a soft topography; however it presents a quite irregular land. In "Figure 7(a)" the complete geometry of the Belo Horizonte map digitalized in CFX is presented. "Figure 7(b)" shows a view of the acceleration of the velocity for the highest plan of the area of Belo Horizonte, visualizing clearly the compression of the atmospheric boundary layer (red area).



(a) (b)

Figure 7 – (a) Topographical domain digitalized in CFX and (b) Velocity acceleration of the highest plan of the Belo Horizonte map

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 won 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 server with double processor and even 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.

Zhang, Y.Q., Arya, S.P., and Snyder, W.H., 1996, "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.

AEA Technology plc. CFX-5.5, 2002, Documentation. AEA Technology Engineering Software Ltd, United Kingdom.

Andreas, E.L., 1996, "The atmospheric boundary layer over polar marine surfaces", US Army Corps of Engineers

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

Kim, H.G, Lee, C.M., and Noh, Y.J., 1998, "Numerical prediction of the wind flow over hilly terrain".

Martins, M.A., 2002, "Estimativa de erro e adaptatividade para métodos de volumes finitos em malhas triangulares não estruturadas", Tese de Doutorado, Departamento de Engenharia Mecânica, UFMG, Belo Horizonte.

Montavon, C., 1998, "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.

Raithby, G.D. and Stuble, G. D., 1985, "Prediction and Comparison with Experiment of Three-Dimensional Flow over the Askervein Hill". Rep. Thermal Science Ltd., Waterloo, Ont. Canada.

Rhie, C.M., and Chow, W.L., 1982, "A numerical study of the turbulent flow past as isolated airfoil with Trailling edge separation", AIAA J., vol. 21.

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.

Uchida, T. and Onya, Y, 999, "Numerical Simulation of Atmospheric Flow Over Complex Terrain", Journal of Wind Engineering and Industrial Aerodynamics, vol. 81, p. 283-293.

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