FOREST EDGE WIND FLOW

Dias, Nuno Jorge Sousa, njsdias@gmail.com
Brasil, Antonio César Pinho, brasiljr@unb.br
University of Brasilia. Department of Mechanical Engineering. 70910-900 Brasília, DF.

Silva, Glécia Virgolino da, gleciavs@gmail.com
University of Brasilia. Department of Mechanical Engineering. 70910-900 Brasília, DF.

Abstract. *In this work the wind flow at forest edges is studied by using the commercial code FLUENT. The study of the wind behavior at forest edges is important to areas such as biology and forest management. The turbulence of the wind flow at forest edges was computed with a k-ε model. The standard constant values of the model were changed. Source terms were added to the equations momentum, turbulent kinetic energy and its dissipation rate. These modifications are necessary to represent the forest and capture the influences of the forest in the wind flow. The model was capable to represent the turbulence and the shape of the wind flow at the edges. As expected, the effects of drag coefficient have revealed lower velocities for higher drag coefficient values. The numerical results obtained at the edges and within the forest are in agreement with experimental field data.*

Keywords: *Forest Edge, k-ε model, Numerical Simulation.*

1. INTRODUCTION

The studies of wind flow on canopies have been motivated by the interest in quantifying the contributions of forests on the climate and on local ecosystem. The characterization of flow in forests provide assistance to areas such as biology, hydrology, agriculture and meteorology (Raupach and Thom, 1981). Studies at forest-atmosphere interface can estimate the fluxes of gases, temperature field and moisture. The magnitude of these quantities are better computed if the velocity profile and the turbulence quantities are known.

More complex models are necessary to describe heterogeneous forests. This spatial variability is due to the presence of clearings, roads and deforested areas that origin forest edges (Dupont and Brunet, 2008). The presence of a recirculation zone at the exit of the forest promotes damage, which influence directly plants and animals, micro-climate and ecosystem processes (Zheng *et al.*, 2005). However, according to Cassiani *et al.* (2008) this area of recirculation appears only for leaf area index greater than 4. Flesch and Wilson (1998) studied the size of clearings based on the existence of regions with weak winds at the exit edge of the forest. For these authors, the shield effect caused by trees in function of clearing size can be used for cultivation and plantation of young trees.

Three methodologies are applied to study the phenomena presented above: field experiment, wind tunnel experiment and numerical simulation. In order to study complex scenarios, computer technology advances make numerical simulation the most attractive methodology, helping the understanding of flow dynamics in the forest (Clark *et al.*, 2007).

The turbulence of the wind flow within and above forest was computed with a *k-ε* model. Svensson and Haggkvist (1990) added sources terms to equations momentum, turbulent kinetic energy and its dissipation rate to account drag forces caused by the forest. Foudhil *et al.* (2004) proposed a *k-ε* turbulent model to predict the turbulence and fluxes of gases in heterogeneous forests. Liang *et al.* (2005) developed a three-dimensional *k-ε* model for wind flow in forests. Krzikalla (2005) studied the influence of the geometry of forest edges using the code AQUILON with *k-ε* turbulent model. Hiraoka and Ohashi (2008) developed a *k-ε* model for forecasting heat, water vapor and carbon dioxide on vegetation.

In this work, the effects of the forest edges on wind flow were studied by using the commercial code FLUENT. This was possible by programming the user defined functions (UDF) of FLUENT. By means of UDF was possible to introduce the boundary conditions and source terms for momentum, turbulent kinetic energy and its dissipation rate equations. In order to adapt the *k-ε* model to the wind flow within and above forest, it was necessary to modify the standard constants of the model. The simulated cases were a wind flow entering and leaving the forest. In the first case, the results were compared with field data of Irvine *et al.* (1997) study. In the second case, they were compared with field data of Raynor (1971).

2. MATHEMATICAL MODEL

Flow within and above forest is described by continuity and momentum equations. In this work, the air is a newtonian fluid. The flow is incompressible in neutral atmosphere conditions on land with no topologic variability. Vibration effects of vegetative elements and Coriolis forces were not considered. The treatment of the stochastic turbulent characteristics was made by applying the time-average to instantaneous quantities. Assuming an arbitrary instantaneous value $\left(A\right)$, it was decomposed on its deterministic $\left(\overline{A}\right)$ and stochastic $\left(A'\right)$ terms. A spatial-average is necessary because forest lands are composed by vegetative elements in random distribution. According to Kaimal and Finnigan (1994), this average takes into account an extensive parallel slab in the horizontal direction in order to eliminate the horizontal random distribution, but the slab should be fine enough in the vertical direction to preserve the vertical features of the forest. The spatial-average operator is denoted by a bracket symbol $\langle . \rangle$. This average is explained on the works of Raupach and Shaw (1982) and Finnigan (2000). After applying these two kinds of average, it were obtained continuity, momentum, turbulent kinetic energy (*k*) and its dissipation rate (*ε*) equations for the wind flow in the forest land. These equations are (where *i*,*j*=1,2,3 represent the three vector directions on *x*,*y* and *z* axis):

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

$$\frac{\partial \langle \overline{u_i} \rangle}{\partial t} + \langle \overline{u_j} \rangle \frac{\partial \langle \overline{u_i} \rangle}{\partial x_j} = -\left(\frac{1}{\rho} \frac{\partial \langle \overline{p} \rangle}{\partial x_i} + \frac{2}{3} k \right) + \frac{\partial}{\partial x_j} \left[\left(\nu + \nu_T \right) \left(\frac{\partial \langle \overline{u_i} \rangle}{\partial x_j} + \frac{\partial \langle \overline{u_j} \rangle}{\partial x_i} \right) \right] + S_{u_i} \tag{2}$$

$$\frac{\partial \langle k \rangle}{\partial t} + \langle \overline{u_j} \rangle \frac{\partial \langle k \rangle}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_k} \right) \frac{\partial \langle k \rangle}{\partial x_j} \right] + G_k - \varepsilon + S_k \tag{3}$$

$$\frac{\partial \langle \varepsilon \rangle}{\partial t} + \langle \overline{u_j} \rangle \frac{\partial \langle \varepsilon \rangle}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_\varepsilon} \right) \frac{\partial \langle \varepsilon \rangle}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} G_k - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + S_\varepsilon \tag{4}$$

The Reynolds tensor $\left(-\overline{u_i' u_j'} \right)$ arises when the time-average is applied to the governing equations. Usually, for the wind flow in the forest, the Reynolds tensor is computed without the anisotropic part:

$$-\overline{u_i' u_j'} = 2 \nu_T S_{ij} \tag{5}$$

The mean rate of strain tensor is given by:

$$S_{ij} = \frac{1}{2} \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \tag{6}$$

The turbulent viscosity $\left(\nu_T \right)$ was modeled by Boussinesq hypothesis, where C_μ is a constant of the model:

$$\nu_T = C_\mu \frac{k^2}{\varepsilon} \tag{7}$$

The production of the *k* term is modeled as:

$$G_k = -\langle \overline{u'_i u'_j} \rangle \frac{\partial \langle \overline{u_i} \rangle}{\partial x_j} = \left[\nu_T \left(\frac{\partial \langle \overline{u_i} \rangle}{\partial x_j} + \frac{\partial \langle \overline{u_j} \rangle}{\partial x_i} \right) \right] \frac{\partial \langle \overline{u_i} \rangle}{\partial x_j} \tag{8}$$

When we apply the spatial-average, new terms named as source terms arise on the equations. These source terms are function of two main forest characteristics: drag coefficient $\left(C_d \right)$ and leaf area density $\left(a \right)$. The latter is a function of height. For momentum, *k* and *ε* equations, the source terms are, respectively:

$$S_u = -C_{dm} C_d a \left| \langle \overline{u_i} \rangle \right| \langle \overline{u_j} \rangle \tag{9}$$

$$S_k = C_{pkw} C_d a \left| \langle \overline{u_i} \rangle \right|^3 - C_{dkw} C_d a \left| \langle \overline{u_i} \rangle \right| k \tag{10}$$

$$S_{\varepsilon} = C_{p\varepsilon w}\frac{\varepsilon}{k}C_d a\left|\left\langle\overline{u_i}\right\rangle\right|^3 - C_{d\varepsilon w}C_d a\left|\left\langle\overline{u_i}\right\rangle\right|\varepsilon \tag{11}$$

The S_u represents the momentum absortation rate by vegetative elements due to form and viscous drag. S_k is the net *k* loss rate due to the forest. S_{ε} is the net dissipation rate of *k* loss rate due to the forest. In order to adjust the turbulent model *k-ε* to the wind flow above and within the forest, it is necessary to change the values of the model standard constants. Following the approach of Katul *et al.* (2004), for relations among standard deviations (σ_u, σ_v, σ_w) and friction velocity (u_*):

$$\sigma_u/u_* = 2.4 \quad ; \quad \sigma_v/u_* = 2.1 \quad ; \quad \sigma_w/u_* = 1.25 \tag{12}$$

we obtain:

$$C_\mu = \frac{1}{\left(0,5\left[\left(\sigma_u/u_*\right)^2 + \left(\sigma_v/u_*\right)^2 + \left(\sigma_w/u_*\right)^2\right]\right)^2} = 0.03 \tag{13}$$

Assuming steady state, fully developed flow and production of *k* equals to its dissipation rate, we can deduce the constants:

$$\sigma_\varepsilon = \frac{\kappa^2}{\sqrt{C_\mu}\left(C_{\varepsilon 2} - C_{\varepsilon 1}\right)} = 2.12 \tag{14}$$

$$\sigma_k \approx \frac{\kappa^2}{\sqrt{C_\mu}} = 1.018 \tag{15}$$

where κ is Von Karman constant ($\kappa = 0.42$).

Following Liu *et al.* (1996), $\beta_p = 1$, and Sanz (2003) equations, we can calculate the constants:

$$\beta_d = \sqrt{C_\mu}\left(\frac{2}{0.05}\right)^{2/3}\beta_p + \frac{3}{\sigma_k} = 5.03 \tag{16}$$

and

$$C_{\varepsilon 4} = C_{\varepsilon 5} = \sigma_k\left[\frac{2}{\sigma_\varepsilon} - \frac{\sqrt{C_\mu}}{6}\left(\frac{2}{0,05}\right)^{2/3}\left(C_{\varepsilon 2} - C_{\varepsilon 1}\right)\right] = 0.78 \tag{17}$$

So, the constants for turbulent model and for source terms are:

$$C_\mu = 0.03,\ C_{\varepsilon 1} = 1.44,\ C_{\varepsilon 1} = 1.92,\ \sigma_k = 1.018,\ \sigma_\varepsilon = 2.12, C_{dm} = 1,\ C_{pkw} = 1,\ C_{dkw} = 5.03,\ C_{p\varepsilon w} = 0.78,\ C_{d\varepsilon w} = 3.92$$

3. RESULTS

The main objective of this work is the study of wind flow at the forest. The results of the flow entering the forest land were compared with field data of the Irvine *et al.* (1997) study; and the results of flow leaving the forest were compared with field data of the Raynor (1971) study. For simulations, FLUENT 6.3.26 was used and the mesh was made in Gambit. The mesh was divided into different regions. This technique allows the setting of boundary conditions at each region. On the inlet boundary, it was imposed the following profiles for velocity, turbulent kinetic energy and its dissipation rate:

$$u(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right),\ k = \frac{u_*^2}{\sqrt{C_\mu}},\ \varepsilon = \frac{u_*^3}{\kappa\left(z + z_0\right)} \tag{18}$$

where z_0 is the roughness length of the clearing ground and u_* is the friction velocity. The friction velocity is defined by $u_*^2 = -u^{'}w^{'}$ (Finnigan, 2000).

On the exit boundary, it was imposed an outflow condition. This condition is appropriate when the flow is fully developed. The outflow boundary condition assumes zero normal gradient for all flow variables except for pressure.

The friction velocity at the ground was computed by the velocity value of vertical adjacent cell. The velocity at the clearing and at the forest ground could be calculated from this friction velocity. The forest ground velocity depends on roughness length and turbulent quantities. The velocity at the top boundary was predefined. From this top velocity, it were calculated the friction velocity, the kinetic turbulent energy and its dissipation rate on the top boundary.

The forest characteristics in the work of Irvine *et al.* (1997) are given by Tab. 1.

Table 1. Characteristics of forest land

Parameter	**Average value**
drag of land (z_0)	0.0028 m
height of forest *(h)*	7.5 m
LAI	2.15
C_d	0.2

(Source: Irvine *et al*. (1997))

The experimental data were taken from positions shown in Fig. 1. The station 1 is installed at -6.1 h distance of the front edge forest, the station 2 is installed at 0 h, the station 3 is installed at 3.6 h and the station 4 is installed at 14.5 h. The LAD of the forest is represented by Fig. 2.

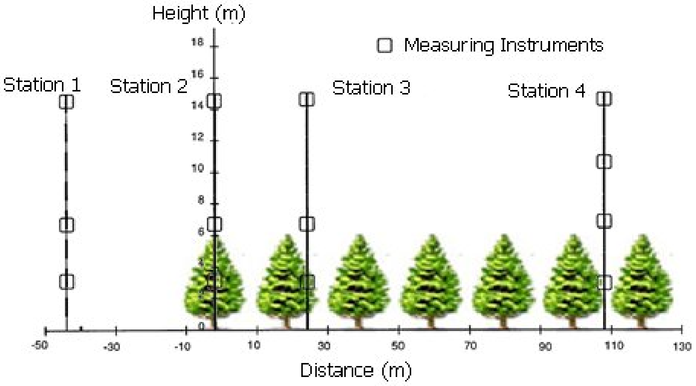


Figure 1. The positions of measuring stations of the Irvine *et al.* experiment (source: adapted of Irvine *et al.* (1997))

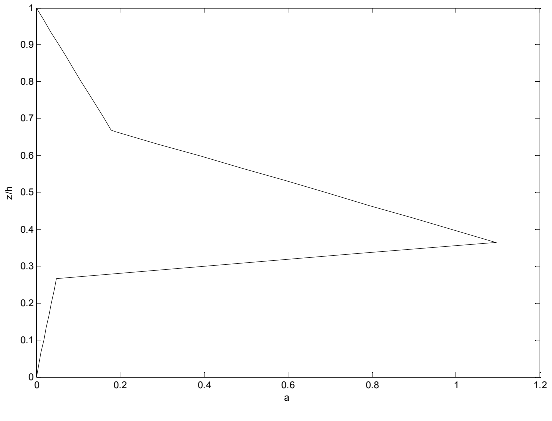


Figure 2. LAD of Irvine *et al.* experiment

Figure 3 represents the dimensions of the computational domain. A mesh with 20,600 nodes was made in Gambit and it is showed in Fig. 4. Figure 5 shows iso-lines of turbulent kinetic energy at the forest front edge. It was observed that higher values of *k* at the forest top happen because vegetative elements break down the mean flow. This breakdown causes eddies with dimensions of the forest height and a higher production of turbulence. Figure 6 shows the iso-lines of the vertical velocity component. When the wind flow reaches the forest front edge, the wind profile changes its shape. This phenomenon is characterized by a high positive vertical velocity. But this velocity is reduced inside the forest, as verified by Dupont and Brunet (2008).

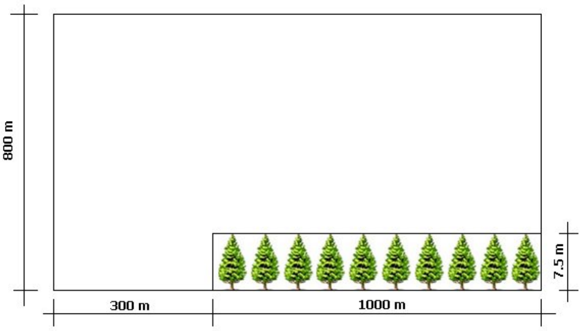


Figure 3. The dimensions of the computational domain for the Irvine *et al.* (1997) study

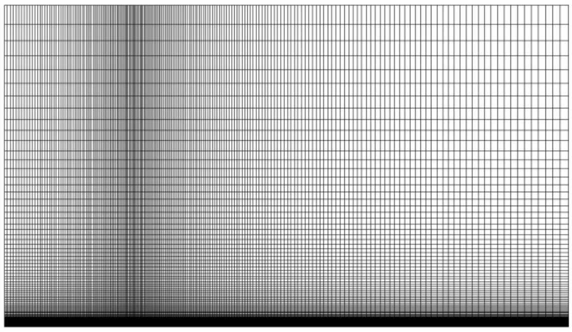


Figure 4. Mesh

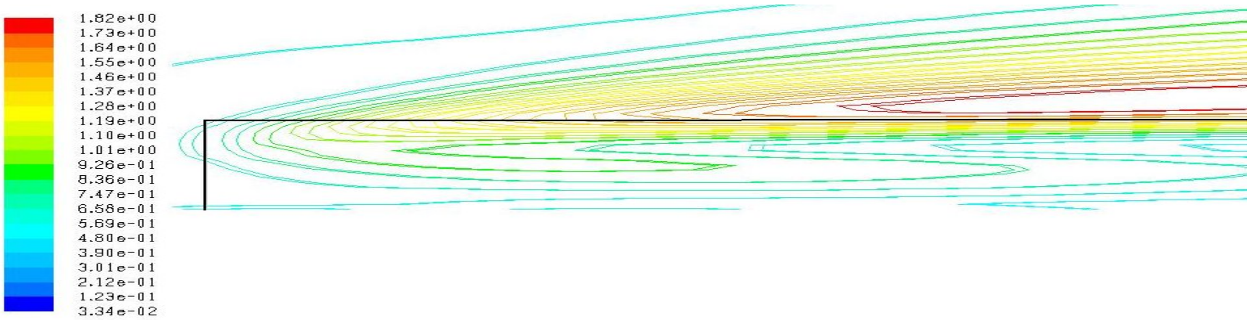


Figure 5. Iso-lines of turbulent kinetic energy at front edge of forest for Irvine *et al* (1997)

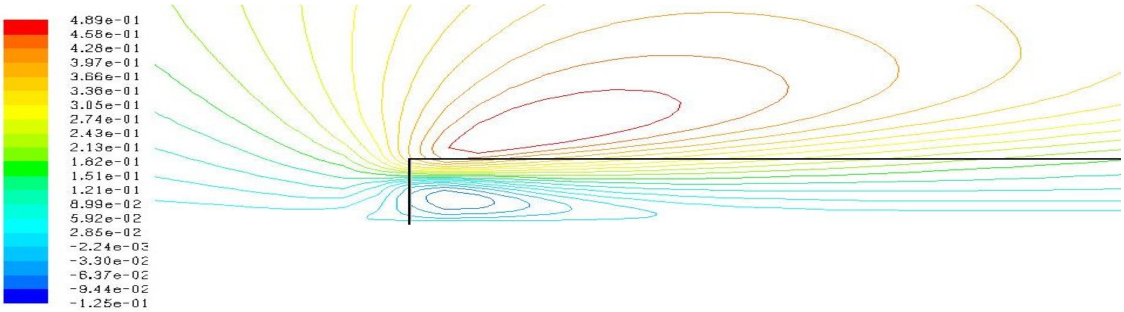


Figure 6. Iso-lines of vertical velocity for Irvine *et al* (1997)

The reference velocity (u_{ref}) is equal to 6.20 m/s in the next set of graphs. This velocity was taken at a height of 2h in station 1. The velocity at the domain top was predefined as 10 m/s. Figure 7 shows the velocity profile at station 1. It can be observed that the flow does not present an inflexion point at a distance of -6.1h. This is typical of lands that have little roughness, where the most part of shear is located close to the ground. Figure 8 shows the velocity profile at station 2. This station is located at the front edge of the forest. It can be observed a velocity reduction due to the forest. Figure 9 shows the velocity profile at the station 3. It is observed that near z/h = 0.5 the velocity is lower. It is due to the maximum of LAD present at that height (see Fig. 2). Figure 9 shows that LAI was well selected due to the agreement among numerical velocities and data field. Figure 10 shows that the model was able to represent, in a reasonable way, the fully developed flow within the forest. Figure 11 shows the velocity profile for three different values of drag coefficients at the station 4. This station was chosen because of the fully developed flow. The typical values of drag coefficients range from 0.1 to 0.3. For a higher value of drag coefficient, it is observed a lower velocity. For the three values of drag coefficient the velocity is the same above the top of florest.

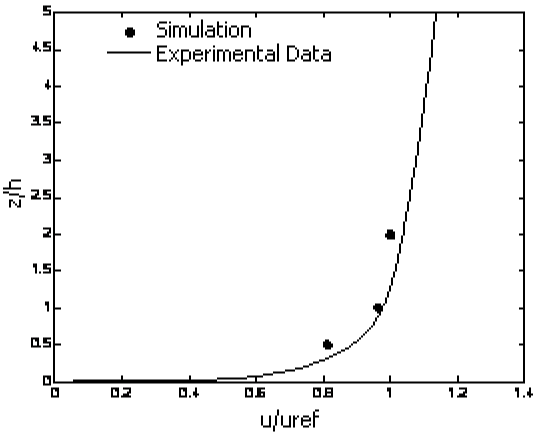


Figure 7. The velocity profile at the station 1 (-6.1h)

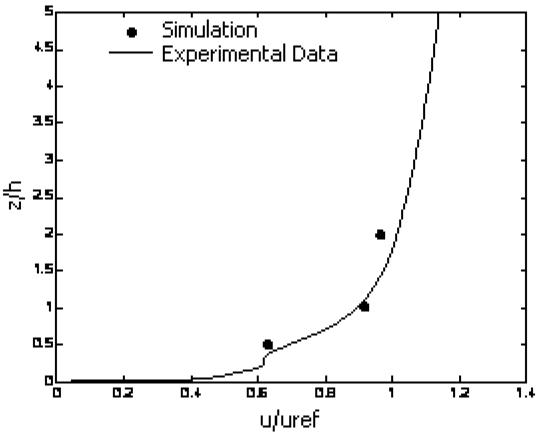


Figure 8. The velocity profile at the station 2 (0h)

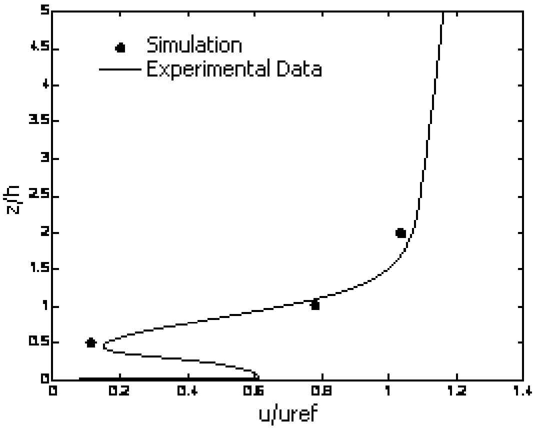


Figure 9. The velocity profile at the station 3 (3.6h)

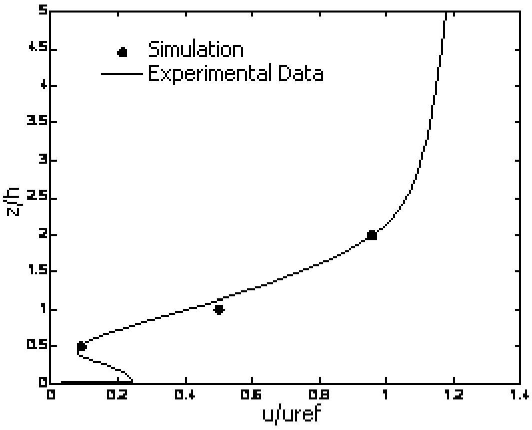


Figure 10. The velocity profile at the station 4 (14.5h)

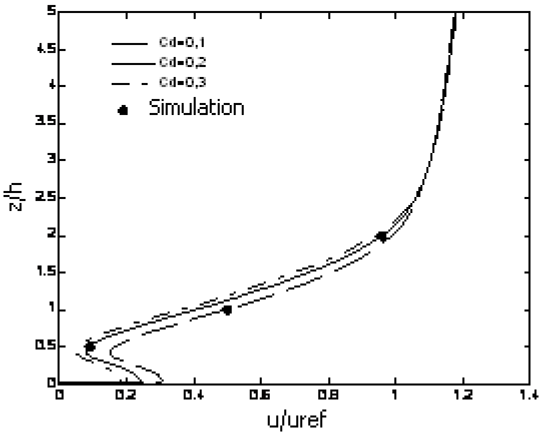


Figure 11. The influence of the drag coefficient on the velocity profile

The second case studied was the wind leaving the forest. The experimental data was obtained by Raynor (1971). The forest was composed by pine trees which had average height of 10.5m. The clearing has a roughness length of 0.1 m and the forest has a C_d equal to 0.15 m. Figure 12 shows five different locations where data was collected. The velocity at the top domain was predefined as 9 m/s. The reference velocity was 3m/s at a heigth of z/h=1.33 for station 1. Figure 13 shows the size of the computational domain. The LAD of the forest is represented by Fig. 14. Figure 15 shows that the inflection point disappears downstream the exit edge, and by analogy with Fig. 16, it can be seen the mixing zone.

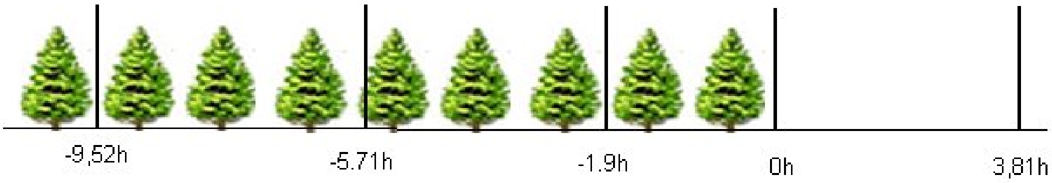


Figure 12. Location of the data stations

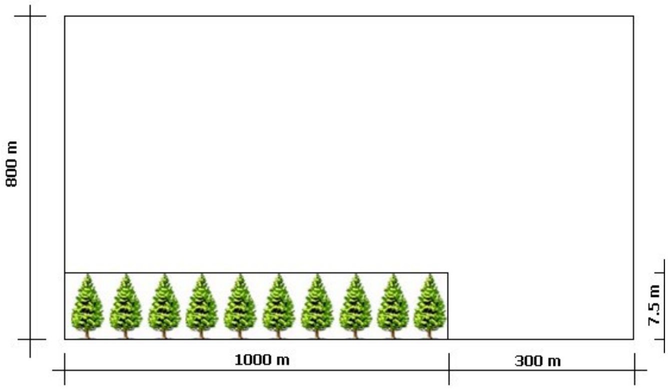


Figure 13. The computational domain dimensions for the Raynor (1971) study

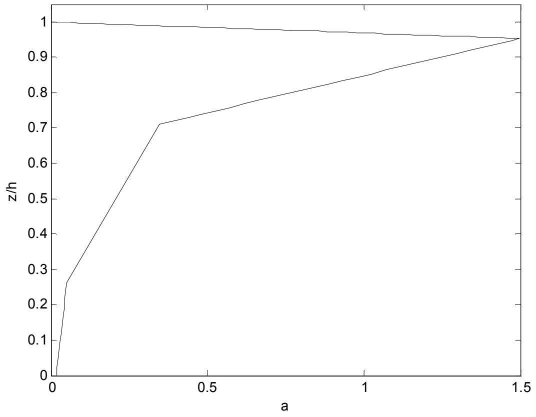


Figure 14. The LAD for the Raynor (1971) study

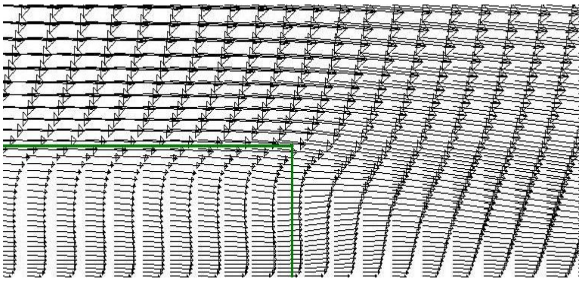


Figure 15. The horizontal velocity at the exit edge

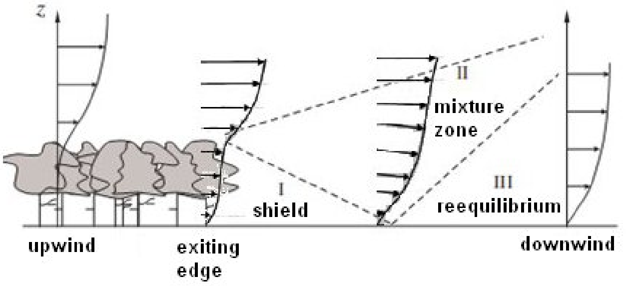
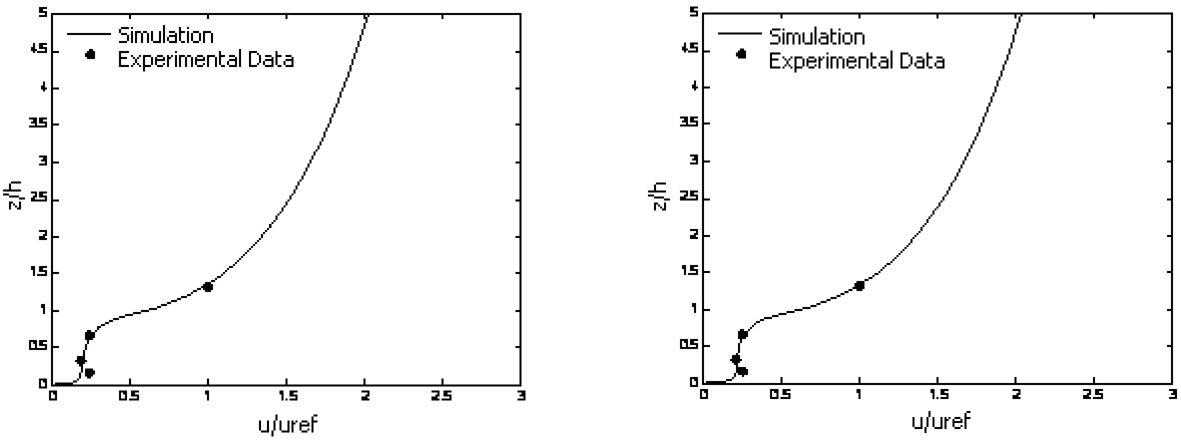
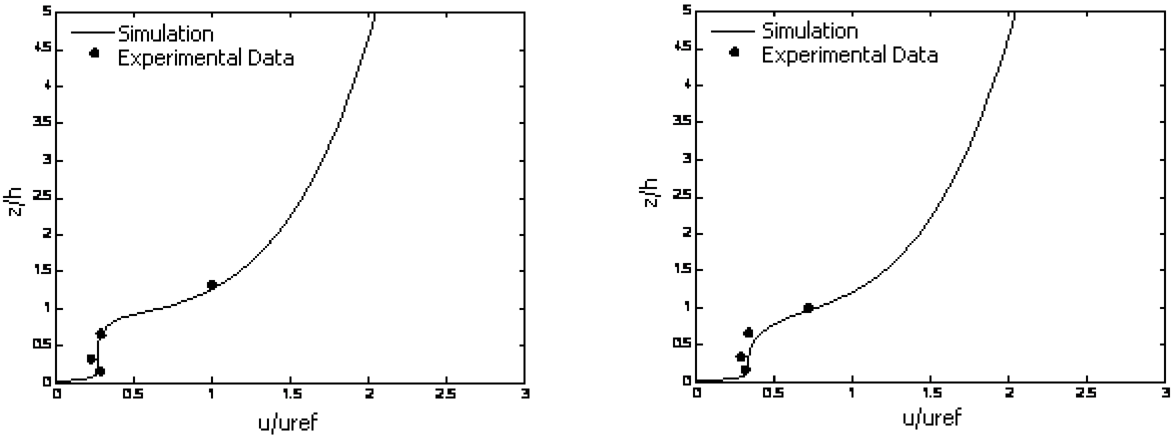


Figure 16. The horizontal velocity at the exit edge (source: adapted from Krzikalla (2005))

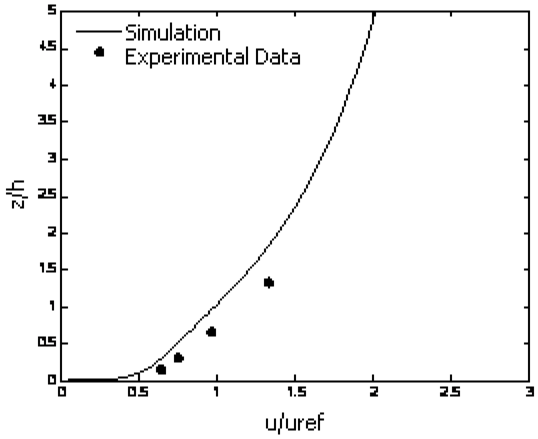
Figure 17 shows a set of graphics which represents the velocity profile for each location in the Fig.12. The agreement between numerical results and experimental data shows that the turbulent model has simulated well the main flow features in forest and clearing regions. Near the exit edge of the forest, the velocity profile remains the same because the flow is fully deleloped. Downstream the exit edge, the velocity profile is quasi-logarithmic due to the absence of forest cover. This is common for flow in areas that are not forested.



a) The velocity profile at x/h=-9.52 b) The velocity profile at x/h=-5.71



c) The velocity profile at x/h=-1.9 d) The velocity profile at x/h=0



e) The velocity profile at x/h=40

Figure 17. The velocity profile at the five regions

4. CONCLUSIONS

The flow within and above the heterogeneous forest land was computed with a modified *k-ε* turbulent model. In order to calculate this flow, it was necessary programmig the UDF of the commercial software FLUENT. The numerical results was compared with field data.

It was observed that an inflexion point appears in the velocity profile when the flow approaches the forest. This inflexion point arises because the magnitude of velocity is not the same between above and below the forest top.

A high magnitude of vertical velocity was observed when the flow enters in the forest. It was verified that the higher values of turbulent kinetic energy are at the forest top. This is because the vegetative elements break down the mean flow. The lower velocity observed within forest is due to the flow velocity reduction that is caused by vegetative elements. This results in a momentum loss.

Near the forest exit edge, it was observed that the horizontal velocity profile is almost the same because the flow is fully developed. Downstream to the forest exit edge (clearing region), it was observed that the velocity profile does not have the inflexion point and it is quasi-logarithmic. This is common for flow in lands that are not forested.

Despite the fact that velocities are understimated, it was observed that the modified k-ε turbulent model was able to represent the velocity field in a heterogenous forest. This underestimation is due to the assumption of isotropy turbulence.

5. REFERENCES

Cassiani, M., Katul, G. G., Albertson, J. D., 2008, “The Effects of Canopy Leaf Area Index on Airflow Across Forest Edges: Large-eddy Simulation and Analytical Results”, *Boundary-Layer Meteorology*, 126: 433-460.

Clark ,T. L. Mitchell , S. J., Novak, M., 2007, “Three-dimensional simulations and wind tunnel experiments on airflow over isolated forest stands”, Boundary-Layer Meteorol., 125:487–503.

Dupont, S., Brunet, Y., 2008, “Impact of forest edge shape on tree stability: a large-eddy simulation study”, Forestry, Vol. 81, No. 3.

Finnigan, J. J., 2000, “Turbulence in Plant Canopies”, J. Annu. Rev. Fluid Mech., 32:519–571.

Foudhil, H., Brunet, Y J., Caltagirone,J.P., 2005, “A Fine-Scale k−ε Model for Atmospheric Flow over Heterogeneous Landscapes.”, Environmental Fluid Mechanics, 5: 247–265.

Clark ,T. L. Mitchell , S. J., Novak, M., 2007, “Three-dimensional simulations and wind tunnel experiments on airflow over isolated forest stands.”, Boundary-Layer Meteorol., 125:487–503.

Flesch, T. K., Wilson, J. D, 1998, “Wind and remnant tree sway in forest cutblocks. I. Measured winds in experimental cutblocks”, Agricultural and Forest Meteorology, 93:229-242.

Hiraoka, H., Ohashi, M., 2008, “A k–ε turbulence closure model for plant canopy flows”, J. Wind Eng. Ind. Aerodyn.

Irvine, M.R., Gardiner, B.A., and Hill, M.K., 1997, “The evolution of turbulence across a forest edge”, Boundary-Layer Meteorology, vol. 84, 3:pp. 467–496.

Kaimal J.C., Finnigan J.J., 1994, ”Atmospheric Boundary Layer Flows: Their structure and measurement”. Oxford University Press, New York.

Katul, G.G., Mahrt, L., Poggi, D., Sanz, C., 2004, “One- and two-equation models for canopy turbulence”, Boundary-Layer Meteorology, vol. 113, 1:pp. 81–109.

Krzikalla, F., 2005, “Numerical Investigation of the Interaction between Wind and Forest under Heterogeneous Conditions”, Institute for Hydromechanics University of Karlsruhe.

Irvine, M. R., Gardiner, B. A., Hill, M. K , 1997, ”The Evolution of Turbulence Across a Forest”, Boundary-Layer Meteorology, 84: 467–496.

Liu, J., Chen, J. M., Black, T. A., Novack, M. D., 1996, “E-ε modelling of turbulent air flow downwind of a model forest edge”, Boundary-Layer Meteorology, 108:21-44

Liang, L., Xiaofeng, L., Lin Borong, L., Yingxin, Z., 2005, “Improved k– e two-equation turbulence model for canopy flow”, Atmospheric Environment, 40:762–770.

Raupach, M. R. ,Shaw, R.H., 1982, “Averaging procedures for flow within vegetation Canopies”, Boundary-Layer Meteorol., 22: 79–90.

Raupach, M. R., Thom, A. S., 1981, “Turbulence in and Above Plant Canopies”, Annu. Rev. Fluid Mech.,13:97-129.

Raynor, G., 1971, “Wind and temperature structure in a coniferous forest and a contiguous field”, For. Sci., vol. 17:pp. 351–363.

Svenssson, U., Haggkvist, K. , 1990, “A Two-Equation Turbulence Model for Canopy Flows”, Journal of Wind Engineering and Industrial Aerodynamics, 35 : 201-211.

Zheng, D., Chen, J., LeMoine, J.M, Euskirchen, E.S., 2005, “Influences of land- use change and edges on soil respiration in a managed forest landscape”, For. Ecol. Manage., 215:169–182.

6. RESPONSIBILITY NOTICE

The authors are: Dias, Nuno Jorge Sousa and Brasil, Antônio César Pinho.