WIND TUNNEL SIMULATIONS OF AIRFLOW WITHIN AND ABOVE OF THE HOMOGENEOUS EUCALYPTUS FOREST STRUCTURE

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Abstract. *In this work wind tunnel simulations of airflow within and above homogeneous eucalyptus stand were carried out in order to study the flow patterns. The mean wind velocities and turbulence intensity were measured on a vertical plane within and above of the eucalyptus forest scale model. For the oncoming flow, two incident wind velocities in the frontal edge of the forest were considered. In the experimental simulations the data corresponded to a forest of height 0.215 m and the domain was represented by a eucalyptus homogeneous forest of 21.44 m. The aim of this work was to investigate the flow patterns eucalyptus forest of FIBRIA Celulose S.A., which is a Company located in Aracruz, ES, Brazil. The results show that vertical profiles of mean velocity contained an inflection point, which dominates the vertical transport of momentum through the dossel layer.*

Keywords: *forest flow, turbulence, wind tunnel simulations, eucalyptus*

1. INTRODUCTION

Wind predictions play an important role in scalar fluxes (mass, momentum, heat, carbon dioxide, etc.) within and above a forest (Raupach *et al*., 1996). Information about wind field within and above the canopy is important in meteorological, agricultural, wind energy industry and forest management. A number of experimental researches for predicting the forest wind flow have been developed (Novak *et al*., 2000). However, accurate prediction of wind field is difficult due to the complex architecture of forest (leaves, branches and trunk) and the complex process of air momentum transport within the canopy boundary layer (Finnigan, 2000).

Various wind tunnel and field experiments as well numerical studies have been performed for investigating the flow within and above forest canopy (Chen *et al*., 1995; Liang *et al*., 2006; Hiraoka and Ohashi, 2008). Novak *et al*. (2000; 2001) carried out field and wind tunnel experiments on the canopy flow with different tree densities. This study was focused on reporting systematic variations of turbulence statistics such as shear stress, turbulence intensity, skewnesses and kurtosis of the plant canopies. The measurements indicate that turbulence in the canopy was dominated by large-scale structures with dimensions of the same order as the height of the canopy. The authors reported that the turbulence flow structure resembles a mixing layer than a boundary layer.

Phaneuf *et al*. (2004) presented a comparison between the predictions using the standard κ-ε, RNG κ-ε and realizable κ-ε turbulence models with wind tunnel experiments for wind flow within and above forest areas with clearings. They found that the turbulence models were able to reproduce quantitatively the features of wind velocities observed in the tunnel experiments. Dalpé and Masson (2009) performed out numerical simulation of flow near forest edge for the purpose of wind energy applications. The results show that proposed method has a good agreement with the wind velocity and turbulence intensity measured experimentally, with average relative errors around 11%.

Wuyts *et al*. (2008) performed out wind tunnel experiments in order to investigate the impact of forest edge structure on edge patterns of wind speed, turbulence and atmospheric deposition. The experiments were conducted with eight structure configurations, encompassing combinations of stem densities, crown depths, and edge transitions. In the wind tunnel a thermal anemometer was used to provide mean wind speed within and at the tree top. Subsequent to the wind speed measurements, the anemometers were removed and deposition was simulated during 120 min from 25% NaCl solution. The authors reported that an adjusted layout of forest edges should be able to mitigate the edge on atmospheric deposition, through reducing the deposition enhancement at the edge or the penetration depth of the edge effect.

Many wind tunnel experiments with artificial plant canopies also were performed to produce guidelines for efficient numerical simulations and to study flow characteristics over a variety of homogenous plant canopy. The physical processes involved in the medium and turbulence field obtained in the various researches showed the following features (Raupach *et al*., 1996; Finnigan; 2000): mean wind speeds profiles present an inflexion point at the tree top ($z/h = 1$) forest top, which indicates that is a zone of high shear, above the forest has a logarithmic profile of the inertial boundary layer ($z > 2h$); the forest is a sink of momentum that is absorbed by drag forces (viscous and form drag); from the tree top downwards ($z/h < 1$) the mean wind velocity decays exponentially. The inflection point in the mean wind speed at homogeneous forest top has major importance since it is responsible for the development of large coherent eddies that control most the momentum and scalar transfer of atmospheric-vegetation system (Lu and Fitzjarrald, 1994; Dupont and Brunet, 2008). Raupach *et al*. (1996) proposed to that the atmospheric flow near the top of forest is analogous to a plane mixing-layer flow rather than the boundary layer – the "mixing layer hypothesis- that explained the origin and scale of these eddies.

The purpose of the present study was to predicting the interaction between wind field and eucalyptus homogeneous forest and investigate the influences of forest architecture on the wind velocities.

2. MATERIAL AND METHODS

2.1 – Wind tunnel

The experiments were conducted in an open return atmospheric boundary layer wind tunnel of Ifes, Vitória, E.S. The tunnel has a rectangular-shaped working section, 0.5 m × 2.0 m, and a height of 0.5 m. According with Irwin (1981) wood spires (0.35 m high) and roughness elements (cubical wooden blocks of 0.035 m) were placed upstream of a model forest eucalyptus to create an atmospheric boundary layer similar to that over a forest under neutral conditions, Fig. 1. The mean streamwise velocity has the following power la profile:

$$\frac{U(z)}{U_\delta} = \left(\frac{y}{\delta}\right)^p \qquad (1)$$

where δ = 0.30 m is the atmospheric boundary layer thickness. The velocity profile was fitted with p = 0.30, which corresponds to the velocity profile over forest with tall trees. The mean velocity vertical profiles of the simulated atmospheric boundary layer were measured by a Pitot tube with probe of 3 mm coupled to micromanometer (TSI, model EBT720), Fig. 1.

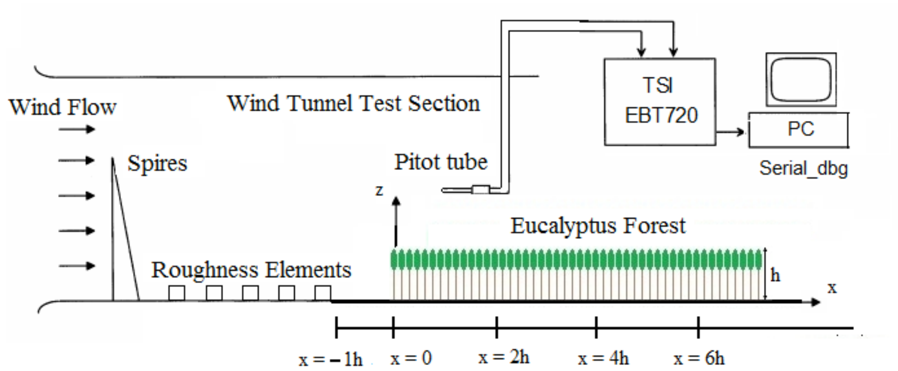

Figure 1. Sketch of the wind tunnel test section, measurement system and forest localization.

The scale model forest was placed behind the roughness elements, at x = -1.0h, extending 1.5 m downstream and spanning the test section. It consisted of artificial scale model trees on average 0.215 m high, crown average diameter of 0.06 m with trunk consisted of iron (diameter of 2.0 mm). The trees were mounted in interlock pattern with a density of 1086 stems m^{-2}. Figure 2 shows the forest scale model within wind tunnel.

Figure 2. Forest with artificial eucalyptus trees within wind tunnel localization.

2.2 Experimental set-up

Orthogonal wind-tunnel coordinates (x,y,z) were defined as along the wind tunnel main axis and increasing downstream (longitudinal flow), with $x = 0$ at the upstream edge of the model forest, horizontal and perpendicular to the x-axis (lateral flow), with $y = 0$ at the centre of the tunnel, and perpendicular to the x-y plane (vertical flow) and increasing upwards and $z = 0$ at the wind tunnel floor, respectively.

Flow velocities in the vertical direction were measured using a Pitot probe and micromanometer (TSI Model EBT 720). The Pitot probe was positioned at x = - 1.0 h; 2.0 h; 4.0 h and 6.0 h, (where h is forest height) within and above the forest model. All profiles consisted of 30 measurements at z = 0.01; 0.03; 0.05, …, 0.37 m and z/h = 1 (the top of the forest). For the oncoming flow, two incident wind velocities in the frontal edge of the forest were considered, which corresponded at Reynolds numbers of 2.8×10^4 and 3.4×10^4. The Reynolds numbers were based on forest height h and wind velocity at the forest height.

3. RESULTS AND DISCUSSION

3.1 Mean and Turbulent Statistics Within and Above Forest

Figures 3 and 4 show the vertical profiles of mean wind velocity normalized in the horizontal axis by velocity at wind speed at the eucalyptus forest height (U_m/U_h) and the vertical axis by forest height (z/h) for Reynolds number 2.8×10^4 and 3.4×10^4 , respectively. The velocity profiles were shown at four positions: upwind at the forest (x = -1.0h) and within and above forest region (x = 2.0h; 4.0h; 6.0h).

At x = -1.0 h the mean velocity profile shows characteristics of the flow in the atmospheric boundary layer in neutral conditions. The flow simulated within was characterized by low velocities within the forest (z/h <1) which show an extraction of momentum by trees; mean wind vertical profile was characterized by an inflection point near the top of the forest (z/h = 1) due to a strong wind shear. The wind velocity profile was logarithmic above the tree top (z/h > 1), which was evident that the shear stress was decreasing in observed logarithmic region. The mean velocity profile suggested an equilibrium state in x/h between 2.0 and 4.0. These experimental results were consistent with literature reported by Raupach *et al*. (1996).

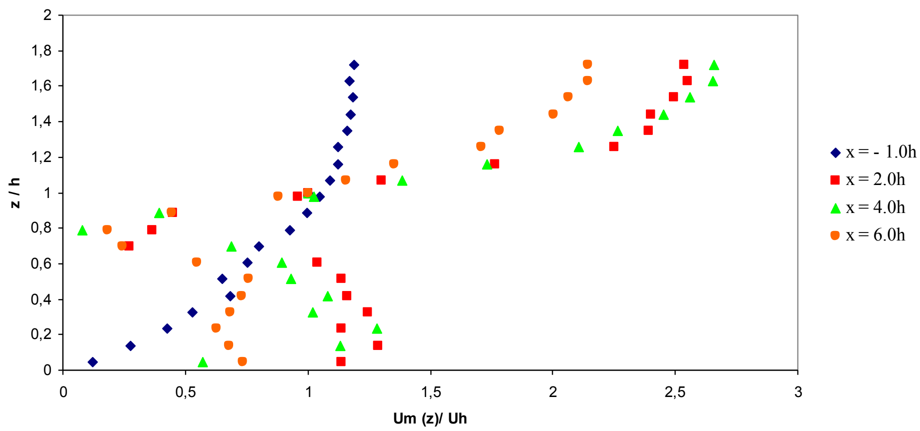

Figure 3. Normalized vertical profiles of mean wind velocity normalized at Re = 2.8×10^4.

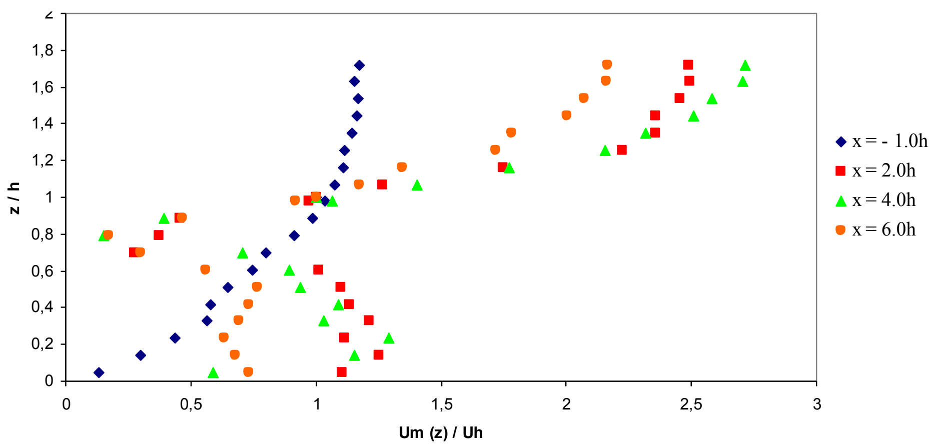

Figure 4. Normalized vertical profiles of mean wind velocity normalized at Re = 3.4×10^4.

Figures 5 and 6 show the vertical profiles of turbulence intensity within and above the forest region for Reynolds number 2.8×10^4 and 3.4×10^4, respectively. The turbulence intensity, σ_u/U_m, where σ_u is the standard deviation of the horizontal wind speed, within and above the forest. The σ_u/U_m at $z = h$ were higher according with values proposed by Raupach *et al*. (1996).

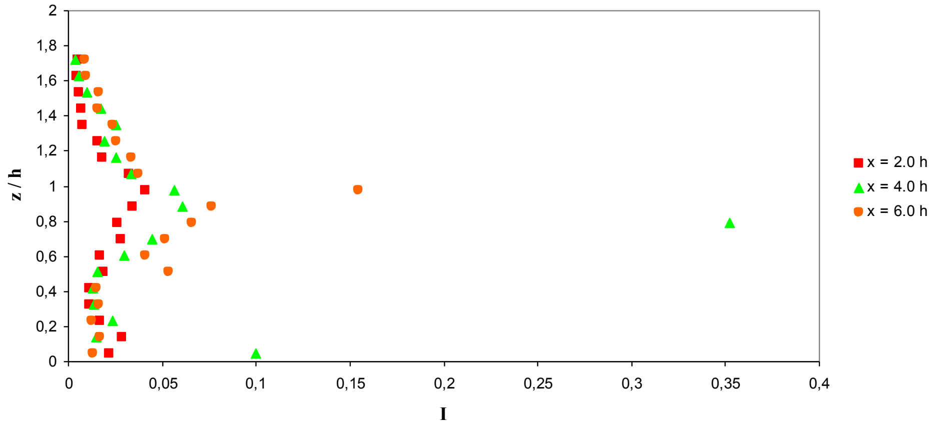

Figure 5. Vertical profiles of turbulence intensity within and above the forest region at Re = 2.8×10^4.

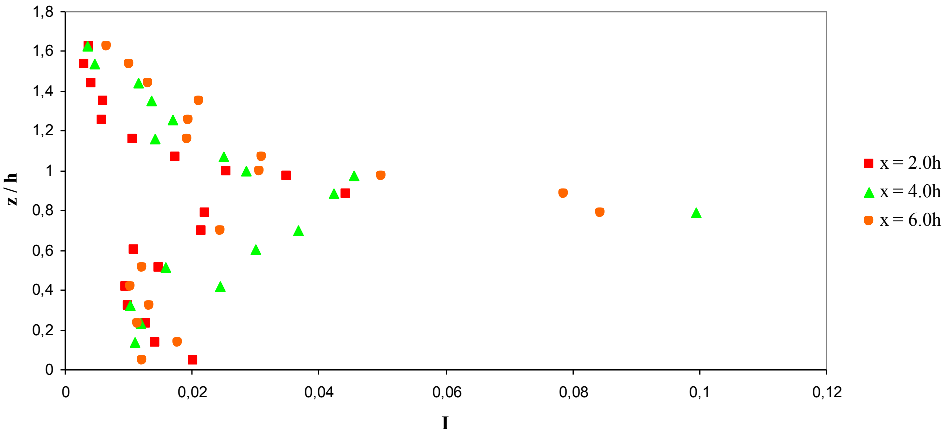

Figure 6. Vertical profiles of turbulence intensity within and above the forest region at Re = 3.4×10^4.

3.2 Evaluating of the Mixing-Layer Analogy

Raupach *et al*. (1996) proposed an analogy to the plane mixing layer as a pattern for atmospheric flow near the top of a forest canopy. This analogy allows explaining various particular features, such as turbulent length scales, the major role turbulent transport and coherent structures at the tree top. One feature of plane-mixing layer for forest flow was the inflected mean velocity profile as a showed in the Figs. 2 and 3. The others features are the shear scale L_s and vorticity thickness δ_ω, given by (Finnigan, 2000):

$$L_S = \frac{U_m(h)}{\left(du_m/dz\right)_{z=h}} \cong \frac{1}{2}\delta_\omega = \frac{1}{2}\frac{\Delta U}{\left(du_m/dz\right)_{\max}} \tag{2}$$

Table 1 shows the shear scale L_s normalized by forest height. According Raupach *et al*. (1996) the L_s/h is in the range from 0.1 to 1. There was a strong inflection in $U(z)$ near the canopy top, where the shear du/dz was maximal, as shows Figs. (3) and (4). The strength of the shear in this point was described by the L_s. The ratio L_s/h remains close to the 0.1-1 range both Reynolds numbers regime in the present work. These results show the similarities with a plane mixing-layer flow with characteristics of neutral boundary layer.

Table 1. Shear scale L_s normalized by forest height.

Authors	h(m)	L_s/h
Present work, Re = 2.8 × 10^4	0.215	0.20
Present work, Re = 3.4 × 10^4	0.215	0.21
Brunet *et al*. (1994)	0.047	0.56
Gardiner (1994)	0.30	0.30
Novak *et al*. (2000)	0.15	0.44

4. CONCLUSIONS

This work presented wind-tunnel measurements of mean wind speed and turbulence intensity within and above uniform scale model eucalyptus canopy. In general, the results agree well with experimental measurements made in other wind tunnel as reported by Raupach *et al*. (1986), Novak *et al*. (2000).

The flow simulated within was characterized by low velocities within the forest (z/h <1) which show an extraction of momentum by trees; mean wind vertical profile was characterized by an inflection point near the top of the forest due to a strong wind shear. The wind velocity profiles above the canopy were roughly approximated by the logarithmic profile. Hence, it was evident that the shear stress was decreasing in observed logarithmic region. The mean velocity profile suggested an equilibrium state in x/h between 2.0 and 4.0.

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