NUMERICAL INVESTIGATION OF THE AIR FLOW THROUGH AND ABOVE THE FOREST CANOPY

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Abstract. . *The k - ε turbulence model was used to examine the air flow both through and above a forest scale model submerged in an otherwise undisturbed boundary-layer flow. The effects of the forest canopy were modeled conventionally by using a sink for momentum. In addition, sources/sink were added to the k- and ε budget equations to account for the additional loss of turbulence energy. When the forest was considered a homogeneous porous media the drag force of the vegetation was parameterized by Darcy and Forchheimer terms. The flow equations were solved using the FLUENT fluid dynamic program. The thermal stratification was not included in the model simulation. Predictions from the model were compared against wind tunnel data, and good agreement was observed. The numerical results were presented together with the wind tunnel data and some useful conclusions were drawn.*

Keywords*: canopy flow, turbulence model, mixing layer analogy, canopy porous media*

1. INTRODUCTION

There are several mathematical models that provide information about the canopy flow. They are receiving attention in numerous fields such as ecology, meteorology, hydrology, climate system modeling and various engineering applications (Raupach et al., 1996, Finnigan 2000; Phaneuf et al., 2004). The ability of theses models to produce numerical predictions of the mean flow (U), turbulent kinetic energy (k), some portioning of k among its three components, and Reynolds stresses (Raupach 1989a; Katul and Albertson, 1999).

Early modeling studies such as the first-order closure models were based on the K-theory (Cowan, 1968; Thom 1971). These models may well reproduce mean velocity (Wilson et al., 1998), but cannot provide second-order statistics. Wilson and Shaw (1977) pointed out that a K-theory model provides little insight into the nature of momentum transport processes within the vegetation canopy. Wilson and Shaw (1977) proposed a second-order closure model in order to identifying the minimum turbulence statistics in the simulation of the canopy flow. In this approach the turbulent kinetic energy and Reynolds stress were solved simultaneously with the momentum equation. However, they are computationally expensive and require complex numerical algorithms for three-dimensional transport problems. In addition, Wilson and Shaw (1977) reported that the calculated velocity profile was sensitive to the parameterization scheme for the turbulent transport in their model.

The k-ε turbulence model is an alternative approach that does not use higher-order closure principles. This model is among the most popular computational models in computational fluid dynamic (Green, 1992; Liu et al., 1995). In this work the standard k-ε turbulence model was used to simulate the canopy flow. Two different methodologies were applied: (I) the source terms due to the drag caused by vegetation were included in the transport equation for the momentum, turbulent kinetic energy (TKE) and its dissipation rate (ε), and (II) the forest was treated as a porous medium. The purpose of the present study is to explore the applicability of the k-ε turbulence model in the modeling of turbulent flow within and above plant canopy. The results of the numerical simulations were compared with experimental dada from wind tunnel (Novak et al., 2000).

2. MODEL FORMULATION FOR THE CANOPY FLOW

The governing equations, in the neutral-stability condition, for solving the flow problem involving a fully developed surface boundary layer within and above the scale forest model are continuity equation and the momentum equations.

2.1 Source terms for the momentum, *k* and ε

The resistance due to the presence of the vegetation and the source terms due to production and destruction of the TKE, were respectively modeled according to Svensson and Haggkvist, (1990):

$$S_u = \frac{1}{2}\rho A(z) C_D |\vec{u}| u_i \quad (1)$$

$$S_k = \frac{1}{2}\rho A(z) C_D |\vec{u}||\vec{u}|^2 \quad (2)$$

$$S_\varepsilon = \frac{1}{2}\frac{\varepsilon}{k} C_{4\varepsilon}\rho A(z) C_D |\vec{u}||\vec{u}|^2 \quad (3)$$

where S_u, S_k, S_ε are the source terms for the momentum, k and ε transport equations in the SKE turbulence model, respectively. C_D is the drag coefficient, $A(z)$ is the leaf area index, and $C_{4\varepsilon} = 1.95$ is an empirical constant (Svensson and Haggkvist, 1990).

2.2. Source Term for the Porous Media Canopy

Treating the forest as a homogeneous porous medium (Finnigan, 2000) the momentum budget equation is parameterized by the Darcy and Forchheimer terms, given by

$$S_u = -\left(\frac{\mu}{K} V_i + C_i \frac{1}{2}\rho V_{mag} V_i\right) \quad (4)$$

where K is the permeability, C_i is the inertial resistance factor, μ is fluid viscosity and V_i and V_{mag} are respectively the three components velocities and magnitude velocity of Darcy.

The values of permeability for the vegetation used in all the calculations executed in this study were determined according to the following equations of the Ergun (1952):

$$K_z = \frac{\phi^3 d_c}{150(1-\phi)^2} \quad (5)$$

$$K_x = \frac{\phi^3 d_h}{150(1-\phi)^2} \quad (6)$$

where K_z and K_x are respectively the permeability in the z and x directions, ϕ is the vegetation porosity, and d_c and d_h are respectively the characteristics length scales of the Reynolds number. In this case d_c is the crown diameter of the vegetation for the flow in the horizontal direction and d_h is the hydraulic diameter for the flow in the vertical direction. The hydraulic diameter is dependent on the spacing S, of among the trees or the diameter ratio of the vegetation and it is determined by:

$$d_h = d_c\left(\frac{4(S/d_c)^2}{\pi} - 1\right) \quad (7)$$

The inertial resistance factor in the Eq. (4) is calculated by (Nield, 2001):

$$C_i = \frac{1}{2}\frac{\phi F}{\sqrt{K}} \quad (8)$$

where F is the Forchheimer constant due to drag pressure, given by (Nield, 2001):

$$F = \frac{1.75}{150^{(1/2)} \phi^{(3/2)}} \quad (9)$$

3. WIND TUNNEL EXPERIMENTS

The wind tunnel experiments were fully described in Novak et al. (2000; 2001) and only the main details of this setup are presented here. Novak et al. (2000; 2001) conducted out experimental studies in the open-return blow-through wind tunnel of the Department of Mechanical Engineering at University of British Columbia (UBC). The wind tunnel has a 25 m long by 1.5 m height and 2.4 m wide working section. The simulation of the turbulent flow in the atmospheric boundary layer in the case of neutral-stability was generated by a combination of vertical spires (Counihan, 1999), transverse board, and wooden blocks placed successively downwind at the inlet section of the wind tunnel with a total length of about 7 m. Orthogonal wind-tunnel coordinates (x,y,z) were defined as along the wind tunnel main axis and increasing downwind (longitudinal flow), with x = 0 at the upwind edge of the model forest, horizontal and perpendicular to the x-y plane (vertical flow) and increasing upwards, with z = 0 at the floor of the tunnel.

A model forest with canopy height (h_f =0.15 m) was constructed with trees made from artificial Christmas tree branches, consisting of two 0.9 mm interwood steel wires supporting 1× 30 mm flat plastic strips that emanated from the wires with cylindrical symmetry. The strips were oriented about 40 mm above the horizontal plane when the tree was mounted vertically, yielding an untrimmed diameter of about 0.045 m. The bottom end of the tree was trimmed so that the lowest 0.015 m above the floor was free of foliage while the upper third was trimmed to a mildly conical shape. The total leaf area per tree was 0.013 m^2 and the frontal area per tree was 0.0043 m^2. The trees were firmly installed into plywood boards drilled with evenly spaced holes in a ‘diamond’ pattern produced by staggering alternate rows along the length of the tunnel (Novak et al., 2000).

Two tree densities were studied: 125 and 31 trees m^{-2}, equivalent to total (one-sided) leaf-area indices, LAI, of 1.7 0.4, respectively, and referred to as dense forest (DF) and sparse forest (SF).

4. NUMERICAL METHOS AND BOUNDARY CONDITIONS

In this study, the commercially available code FLUENT version 6.12.16 was used in the numerical simulations. The flow equations were discretized using a Control Volume Method. The SIMPLE algorithm from Patankar (1980) was used in or to obtain the velocity-pressure coupling, and the Power-Law discretization scheme was used.

The mean velocity profile at inlet was set equal to (Richards and Hoxey, 1993):

$$U(z) = \frac{U_*}{k_v} \ln\left(\frac{z + z_d}{z_d}\right) \quad (10)$$

where k_v is the von Karman constant, U_* is the friction velocity, z_d is roughness length.

According , the inlet profiles for k and ε were specified by (Richards and Hoxey, 1993):

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \quad (11)$$

and

$$\varepsilon = \frac{u_*^3}{k_v(z + z_d)} \quad (12)$$

At the outlet, tangential gradients were set to zero. No-slip conditions were used at the solid surfaces and the symmetry condition was used at the top of the computational domain.

The friction velocity, roughness length, porosity, permeability, hydraulic diameter and Forchheimer constant for the threes investigate forest scale model are listed in Tab. (1).

Table 1. The properties of the dense and sparse canopies.

	DF	SF
u_* (m s^{-1})	0.82	0.81
z_d (m)	0.015	0.014
ϕ	0.84	0.96
K_x	2.59×10^{-4}	6.23×10^{-6}
d_h	0.212	0.991
F	0.18	0.15
K_z	7.28×10^{-3}	3.83

5. RESULTS AND DISCUSSION

In the present study 2-D numerical simulations using the k - ε turbulence model were carried out and the results of the predicted vertical profiles of wind velocity, turbulence intensity and Reynolds stress were compared with wind tunnel data (Novak et al., 2000; 2001).

5.1. Results of the Source Term Methodology

Figure (1) shows the measured and predicted vertical profiles of the flow statistics by using source term methodology for the two canopies, respectively, dense forest (DF) and sparse forest (SF).

In the source term methodology the comparison between modeled and observed mean velocity indicates good agreement in both profile shape and magnitude, as a shows Fig. (1). These results are similar to those reported by Raupach et al. (1996) and Finnigan (2000), which compared different wind profiles for the vegetation canopies, which resembles the common characteristics: (I) from the tree top ($z / h_f < 1$) the mean wind velocity decays exponentially, leading to low velocities inside both the dense and sparse forest. At heights greater than 1.8 h_f was observed the logarithmic profile characteristics of the inertial sub-layer; (II) At the tree top, was observed an inflection point in the mean velocity, which indicates a zone of high shear and inducing instabilities and production of turbulence.

The modelled and observed profiles of the turbulence intensity show that source term methodology simulates σ_u reasonably well. However, the modelled values of σ_u for $0.7 < z / h_f < 1.8$ in the dense forest, and for $0.5 < z / h_f < 1.8$ in the sparse forest showed smaller the measured values.

The predict results of Reynolds stress vertical profiles showed large differences with measured data, for both DF and SF, as a show Figs. (1). However, qualitatively the computed Reynolds stress in both methodologies showed that the momentum was absorbed in the upper half canopy. In addition, the predicted Reynolds stress decreased to almost zero near the ground, which the same behavior as that show the measured data. These discrepancies were caused by the anisotropy of the turbulence. Thus, a possible explanation for these discrepancies is the omission of any anisotropy eddy-viscosity effects within the k-ε modelling approach.

5.2. Results of Porous Media Methodology

Figure (2) shows the measured and predicted vertical profiles of the flow statistics: mean velocity (U), turbulence intensity (σ_u) and Reynoldss stress ($U'W'$), by using porous media methodology for the two canopies, respectively, dense forest (DF) and sparse forest (SF).

The comparisons between simulated and observed velocity vertical profiles present greater differences within vegetation canopy ($z / h_f < 1$) in both, dense forest and sparse forest. However, the predicted wind speed showed an inflection point at the tree top and decreases of mean velocity within of canopy. Upper the trees top the results for both the DF and SP the predicted values showed good agreement with the observation, as a show Fig. (2). In this case the predicted velocity vertical profiles too resemble the many characteristics reported out by Raupach et at. (1996) and Finnigan (2000).

Simulated and observed vertical profiles of σ_u for dense forest showed good agreement for $z / h_f > 1$ and differences for $z / h_f < 1$, as a shows Fig. (2). However, for sparse forest the predicted σ_u reveals differences for $z / h_f > 1$ and good agreement for $z / h_f < 1$.

The similar patter of the Reynolds stress vertical profiles observed in the results of source term methodology were obtained with porous media methodology, as a show Figs. (1) and (2).

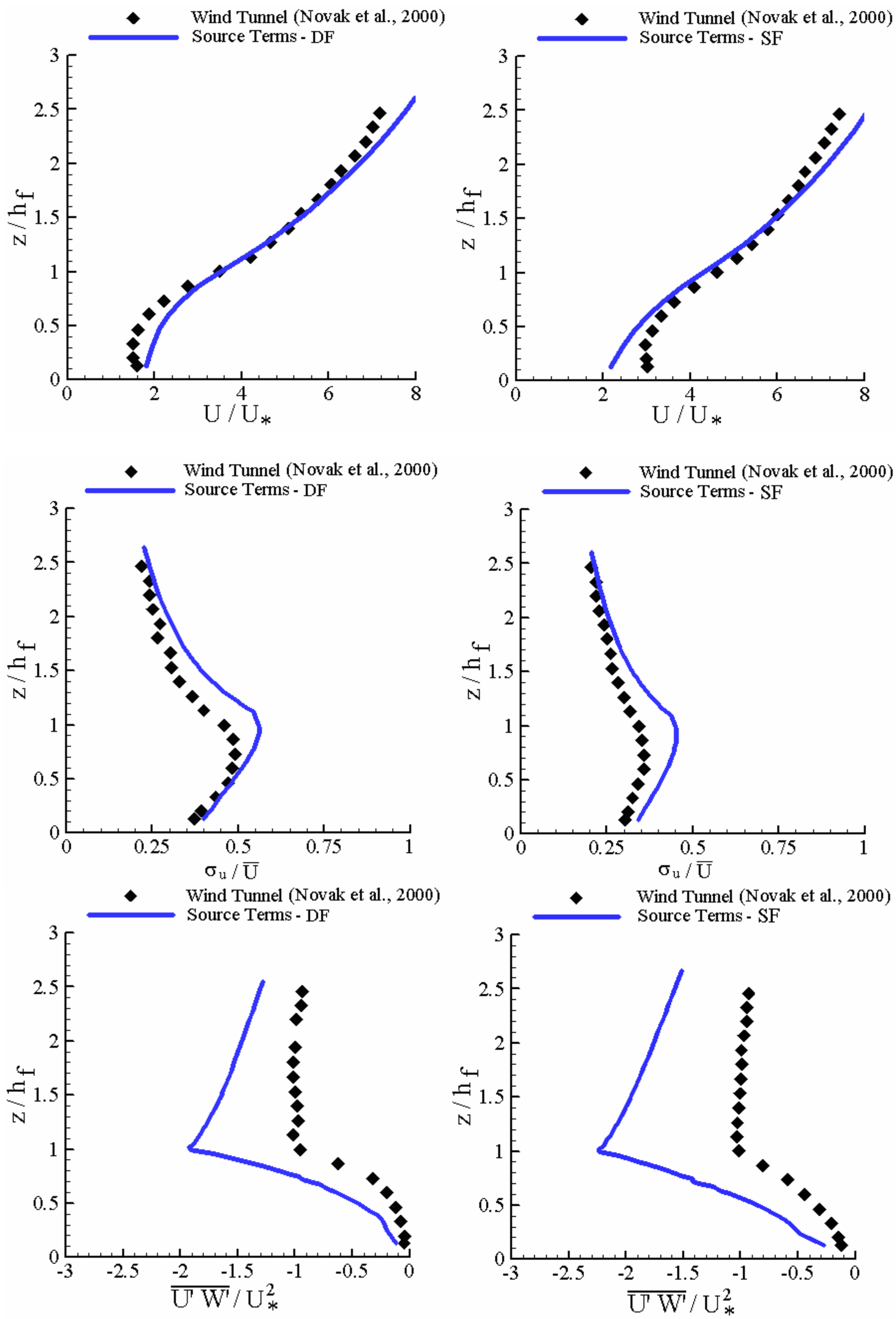

Figure 1. Comparison between measured and modelled flow statistics by using the source terms methodology. Here U is the mean wind speed, σ_u is the turbulence intensity and $U'W'$ is the Reynolds stress. All the variables are normalized by canopy height (h_f) and friction velocity (U_*).

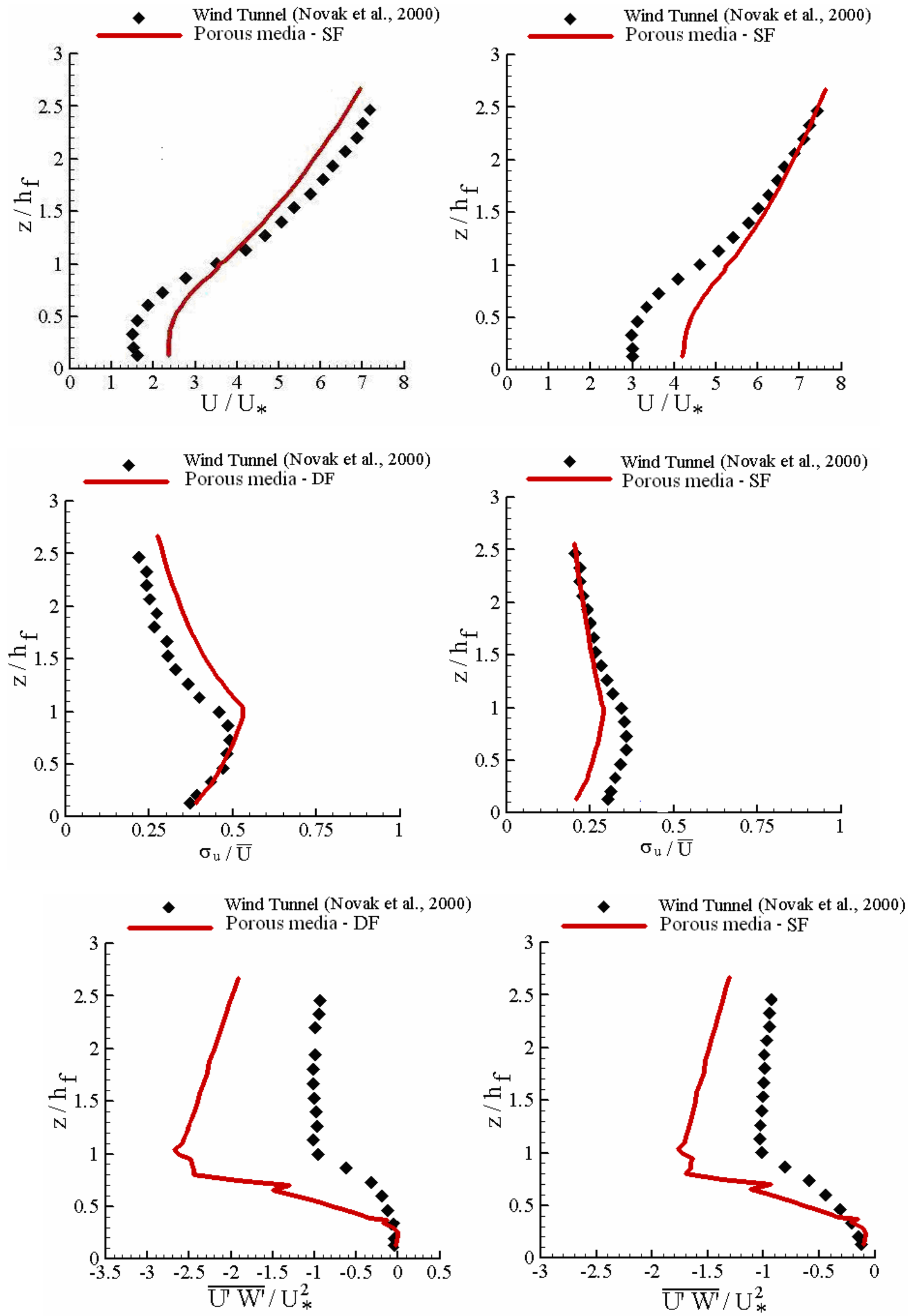

Figure 2. Comparison between measured and modelled flow statistics by using porous media methodology. Here U is the mean wind speed, σ_u is the turbulence intensity and $U'W'$ is the Reynolds stress. All the variables are normalized by canopy height (h_f) and friction velocity (U_*).

5.3. The Mixing Layer Analogy

In flows through of the forest canopy, the vertical discontinuity of the aerodynamic drag results in strong velocity shear at the top of the canopy and greatly increased turbulence intensities in this region, relative to the unobstructed flow (Raupach et al., 1996; Finnigan, 2000).

Raupach et al. (1996) indicated that the canopy flow showed several characteristics of a mixing layer, including the inflection point in the mean velocity profile. Rayleigh proved that a necessary criterion for instability of a parallel flow is that the basic velocity profile has a point of inflection. This condition is satisfied by a hyperbolic tangent profile.

The predicted velocity profiles for all flow scenarios contained an inflection point, as it a showed in Figs. (1) and (2). Thus, qualitatively these results resemble the typical hyperbolic tangent profile of a mixing layer. The typical profile of a mixing layer can be obtained by:

$$\frac{U-\overline{U}}{\Delta U}=0.5\tanh\left(\frac{z-\overline{z}}{2\theta}\right) \tag{13}$$

where U is the mean velocity, $\Delta U = U_2 - U_1$, U_1 and U_2 are respectively, the low and high stream velocities, and θ is the defined by

$$\theta=\int_{-\infty}^{\infty}\left[\frac{1}{4}-\left(\frac{U-\overline{U}}{\Delta U}\right)^2\right]dz \tag{14}$$

where θ is the momentum thickness of the mixing layer.

Figures (3) and (4), show the collapse of the mean velocity profiles for the dense and sparse forest modelled by using the source terms methodology and Figs. (5) and (6) for the porous media methodology. The comparison between the observed velocity profiles and the hyperbolic tangent profiles of a mixing layer was favorable both the source term and porous media methodologies. This results validity the hypothesis that the mixing layer analogy may applicable in the canopy flow.

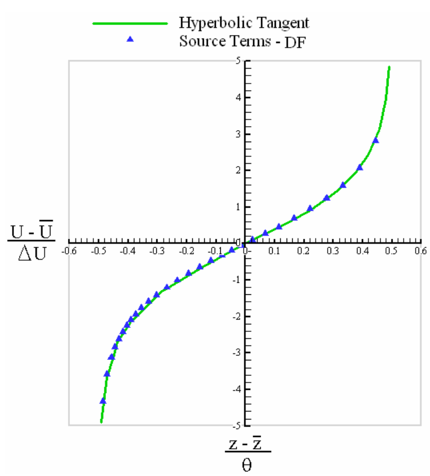

Figure 3. The collapse of the mean velocity profiles for the dense forest modelled by using the source terms methodology. The profiles have been shifted by the mean mixing layer velocity and height (U and z) and normalized by ΔU and the momentum thickness (θ).

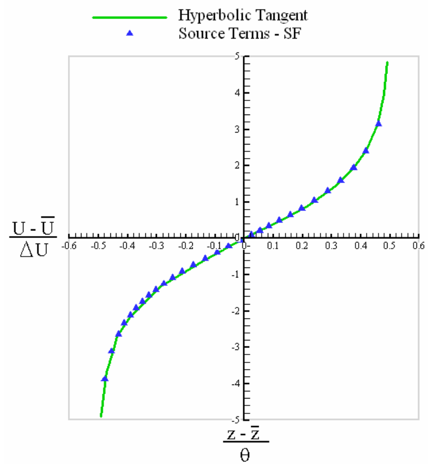

Figure 4. The collapse of the mean velocity profiles for the sparse modelled by using the source terms methodology. The profiles have been shifted by the mean mixing layer velocity and height (U and z) and normalized by ΔU and the momentum thickness (θ).

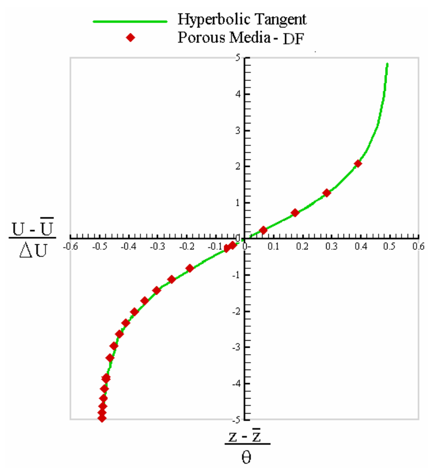

Figure 5. The collapse of the mean velocity profiles for the dense forest modelled by using the porous media methodology. The profiles have been shifted by the mean mixing layer velocity and height (U and z) and normalized by ΔU and the momentum thickness (θ).

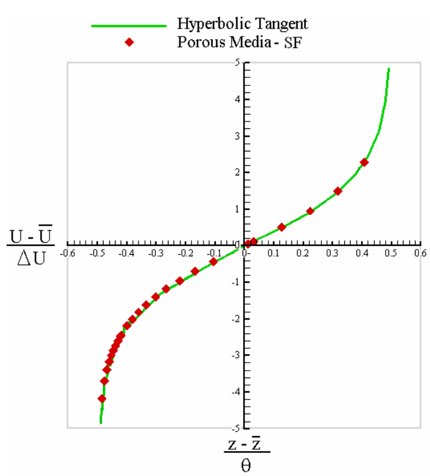

Figure 6. The collapse of the mean velocity profiles for the sparse forest modelled by using the porous media methodology. The profiles have been shifted by the mean mixing layer velocity and height (U and z) and normalized by ΔU and the momentum thickness (θ).

6. CONCLUSION

The results of the predicted wind speeds using the k - ε turbulence model with two different methodologies were able to capture the main characteristics of mean velocity within and above the vegetation canopy. The results of the modelled velocity profiles, obtained by employing the source terms methodology agreed well with measurements in both dense forest and sparse forest. However, the results obtained with the porous media methodology showed smaller discrepancies with the experimental data within the canopy.

The set of simulations for the turbulence intensity provide adequate results when it was compared with data from wind tunnel experiments. However, it was found that the predicted results for the Reynolds stress were sensitive to the parameterization scheme of the standard k - ε turbulence model.

The canopy flow immersed in the roughness sub-layer may be patterned on a mixing layer rather than a boundary layer. The inflection point of velocity profiles resemble the hyperbolic tangent profile of a mixing layer.

The results obtained within this modelling framework strongly encourage the use of the k - ε turbulence model a as useful too for studies of the canopy flow. However, more work has to done on the treatment of canopy-flow interactions, particularly on the analyses of the Reynolds stress due to larger discrepancies obtained.

7. REFERENCES

Couhihan, J., "An Improved Method of Simulating an Atmospheric Boundary Layer in a Wind Tunnel", Atmospheric Environment, Vol.3, pp. 197-214.

Cowan, I.R., 1968, "Mass, heat, and momentum exchange between stands of plants and their atmospheric environment", Quarterly Journal of the Royal Meteorological Society, Vol.94, pp. 523-544.

Ergun, S., 1952, "Fluid flow through packed columns" Chemical Engineering Progress, Vol.84, pp. 89-94.

Finnigan, J.J., 2000, "Turbulence in Plant Canopies". Rewiew of Fluid Mechanics, Vol. 35, pp. 519-571.

Green, S.R., 1992, "Modelling turbulent airflow in a stand of widely-spaced trees", PHOENICS Journal Computational Fluid Dynamic Applied., Vol.5, pp. 294-312

Katul, G.G. and Albertson, J.D., 1998, "An Investigation of Higher-order Closure Models for a Forest Canopy", Boundary Layer Meteorology, Vol.89, pp.47-74.

Liu, J., Chen, J.M., Black, T.A. and Novak, M.D., "E-ε Modelling of Turbulent Air Flow Downwind of a Model Forest Edge", Boundary Layer Meteorology, Vol.77, pp.21-44.

Nield, D.A., 2001, "Some Pitfalls in the Modelling of Convective Flows in Porous Media", Transport Porous Media, Vol.43, pp. 597-601.

Novak, M.D., Warland, J.S., Orcahnsky, A.L., Ketler, R. and Green, S., 2000, "Wind Tunnel and Field Measurements of Turbulent Flow in Forests. Part I: Uniformly Thinned Stands, Boundary Layer Meteorology, Vol.95, pp.457-495.

Novak, M.D., Orcahnsky, A.L., Warland, J.S. and Ketler, R., 2001, "Wind Tunnel Modelling of Partial Cuts and Cutblock Edges for Windthrow" Proceedings of the Windthrow Researches Workshop, Richmond, Canada, pp.176-192.

Patankar, S.V., 1980, "Numerical Heat Transfer and Fluid Flows", Hemisphere Publishing Corporation,

Phaneuf, T.J.; Jackson, P.L.; Wang, Y. and Novak, M.D., 2004, "Two and Three Dimensional Numerical Airflow Modelling Along Forest Edges", 26th Conference on Agricultural and Forest Meteorology, Vancouver, Canada.

Raupach, M.R.; Finnigan, J.J. and Brunet, Y., 1989a, ""Coherent eddies in vegetation canopies", Proceedings of Fourth Australian Conference on Heat and Mass Transfer, Christchurch, New Zeeland, pp. 9-12.

Raupach, M.R.; Finnigan, J.J. and Brunet, Y., 1996, "Coherent eddies and turbulence in vegetation canopies: the mixing layer analogy, Boundary Layer Meteorology, Vol.78, pp. 351-382.

Richards, P.J. and Hoxey, R.P., 1993, "Appropriate Boundary Conditions for Computational Wind Engineering Models Using the k - ε model", Journal of Wind Engineering and Industrial Aerodynamics, Vol.46-47, pp. 145-153.

Svensson, U. and Haggkvist, K.A., 1990, "A Two-equation Turbulence Model for Canopy Flows", Journal of Wind Engineering and Industrial Aerodynamics, Vol.35, pp. 201-211.

Thom, A.S., 1971, "Momentum absorption by vegetation", Quarterly Journal of the Royal Meteorological Society, Vol.92, pp. 414-428

Wilson, J.D., 1988, "A Second-Order Closure Model for Flow through Vegetation", Boundary Layer Meteorology, Vol.42, pp.371-392.

Wilson, J.D. and Shaw, R.H., 1997, "A higher order closure model for canopy flow", Journal of Applied Meteorology, Vol.16, pp. 1198-1205.

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