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Numerical simulation of turbulent kinetic energy downwind of varying-width shelters

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1 Introduction

Windbreaks and shelterbelts appear in many agricultural and forestry scenarios. In a forestry situation where cutblocks alternate with stands, often there is concern about wind-throw both in the remaining trees and for the regrowth. There is strong evidence (Gardiner, 1994) that it is the gustiness, or turbulence, rather than mean wind, which knocks over the trees. Recently Wilson and Flesch (1999) conducted a numerical simulation of varying width shelterbelts within successive cutblocks. One of the conclusions from their work was that turbulence in the cleared area downwind of the wider shelter was *greater* than behind the narrower belt. They explain this phenomenon by suggesting that perhaps the wider shelter provides greater mean wind reduction, leading to greater shear stress and its consequent turbulent energy production. The purpose of this study was to examine the effect of shelterbelt width on both mean and turbulent variables. A wind tunnel model was used in which we generated upstream turbulence resembling an equilibrated forest flow. This was followed by a clearing of $10h$ (where h is tree height), and then the windbreaks, consisting of model trees. Four treatments were run, consisting of 1, 2, 4 and 8-rows of trees. These same configurations were also simulated using the numerical model developed by Wilson et al. (1998).

2 Wind Tunnel

The UBC Mechanical Engineering wind tunnel is an open-return blow-through tunnel 25 m long by 1.5 m high and 2.4 m deep (described in detail by Chen et al. (1995)). Trials were run with turbulent flow simulating the atmospheric boundary layer in neutral-stability conditions. The turbulence was generated by a combination of vertical spires, transverse boards, and wooden blocks placed successively downwind from the inlet. The wooden blocks and model trees were 0.15 m tall (the shelterbelt height, h) and spanned the width of the tunnel. The trees were made from artificial Christmas tree branches with a 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 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.

Four shelterbelt widths were studied: 1, 2, 4 and 8 rows corresponding to $x/h = 0.3, 0.6, 1.2$ and 2.4. Wind speeds were measured at 16 vertical measurement points from $z/h = 0.13$ to 4. Profiles were sampled at $x/h = -1.0$ and -0.3, and at $x/h = 0.3, 1.0, 1.5, 3, 6, 9$ and 18. For the one, two and four row cases, the first three positions downwind were measured at two locations: directly behind a tree and in between the trees in the last row. Profiles at these positions were calculated as the mean of the two locations. The three components of the wind vector (u, v, w) corresponding to the (x, y, z) directions were measured with a tri-axial fibre-film hot-wire probe connected to a constant temperature anemometer system. During the wind tunnel experiments the hot-wire voltages were monitored for 20 s at 500 Hz for each measurement. The mean u at $z = 0.59$ m height was in the range 7.5–8.5 m s^{-1} for all trials.

3 Numerical Model

The numerical simulations used the first-order closure scheme of Wilson et al. (1998) as implemented by Wilson and Flesch (1999). This model parameterizes the eddy diffusivity as $K = \lambda\sqrt{c_e k}$, where λ is a lengthscale, k is the turbulent kinetic energy and $c_e = u_{*0}^2/k_0(h)$ is a constant from the reference equilibrium (1D) case of an infinite forest. The model solves the equations

$$\frac{\partial}{\partial x}\left(\overline{u}^2 - K_a\frac{\partial\overline{u}}{\partial x}\right) + \frac{\partial}{\partial z}\left(\overline{u}\,\overline{w} - K\frac{\partial\overline{u}}{\partial z}\right) = -\frac{\partial P}{\partial x} - c_d a h\overline{u}|\overline{u}| \tag{1}$$

$$\frac{\partial}{\partial x}\left(\overline{u}\,\overline{w} - K_a\frac{\partial\overline{w}}{\partial x}\right) + \frac{\partial}{\partial z}\left(\overline{w}^2 - K_a\frac{\partial\overline{w}}{\partial z}\right) = -\frac{\partial P}{\partial z} \tag{2}$$

$$\frac{\partial}{\partial x}\left(\overline{u}k - K_a\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial z}\left(\overline{w}k - \mu K\frac{\partial\overline{u}}{\partial z}\right) = K\left(\frac{\partial\overline{u}}{\partial z}\right)^2 - \epsilon. \tag{3}$$

using the SIMPLE technique of Patankar (1980).

The grid used ran $85h$ in the x-direction and $8h$ in the vertical. There was a full forest specified at the inflow that ran $25h$, with the windbreaks placed $10h$ downwind of the forest. The inflow was specified by the

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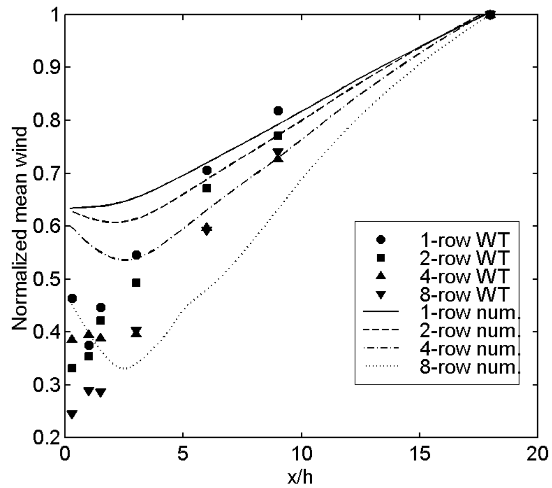

Figure 1: Plots of mean wind u at $z/h = 0.4$, normalized by the the downstream value. Windtunnel simulations shown by symbols, numerical simulations by lines. Horizontal axis shows normalized distance downwind of the shelterbelts.

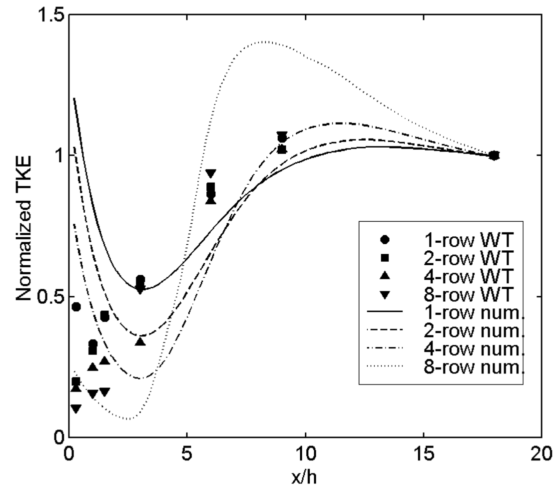

Figure 2: Plots of turbulent kinetic energy k at $z/h = 0.4$, normalized by the the downstream value. Windtunnel simulations shown by symbols, numerical simulations by lines. Horizontal axis shows normalized distance downwind of the shelterbelts.

solution to the 1D equations, outflow was set so that all $\partial/\partial x = 0$, the bottom boundary used the 'law of the wall' with $z_0 = 0.001$, and the top boundary used given momentum flux, $\overline{w} = 0$ and $\partial k/\partial z = 0$. For the trials shown here, a constant drag coefficient of 0.88 was used for forest and shelter.

4 Some Results and Conclusions

Figure 1, showing u with distance downwind from the shelterbelts, shows a greater normalized depression and more rapid recovery in the wind tunnel than in the numerical simulations. Considering that the 1-row case is the only windtunnel run that also shows a distinct minimum downwind of the shelter, we can speculate that perhaps the drag coefficient used in the numerical model was too low. The value used was 0.88, which was the mean of eight measurements on a single tree with a force-moment balance. This value is higher than values determined from full forest data due to the sheltering effect, it is unclear why it might be too low for the numerical simulations. Further runs will examine the effect of a drag coefficient which varies with height.

Similar results are seen in Figure 2, showing the downstream development of k. Again, the 1-row case in the windtunnel is the only one showing the downwind minimum, though all case do show a maximum at around $x/h = 9$, which is more pronounced in the numerical results. In general one sees decreasing k with increasing width in the quiet zone immediately following the shelter, but the maximum downstream values also increase with increasing width. This does suggest, for the type of scenario presented here, that there is some trade-off in selecting a width between the decreased turbulence in the quiet zone and the turbulence in the wake zone. The optimal width for balancing these two factors, based on the limited data presented here, seems to be on the order of $1h$.

Further results from the numerical simulations and wind tunnel data will be discussed in our talk.

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