Forest Modeling

A canopy model for WindSim 4.5

Kassel, 13rd February 2006 – WindSim Workshop
Why the need for a canopy model

(a) Roughness Length $z_0 \, 0.6\,m$

(b) Roughness Length $z_0 \, 0.6\,m$
FOREST WIND PROFILES

\[ u(z) = \frac{u_* \ln \left( \frac{z-d}{Z_0} \right)}{K} \]

\[ u(z) = u(h) e^{\alpha \left( \frac{Z}{h} - 1 \right)} \]

\[ 1 < \alpha < 4 \]

\[ u(z) = \frac{u_{*f} \ln \left( \frac{z-d_f}{Z_{of}} \right)}{K} \]
In the new canopy model of WindSim the Canopy Layer is solved by the use of porosity and drag forces (sinks of momentum).

The canopy is described by:

- Height of the canopy – $h_c$
  - The canopy is discretized with a certain number of cells (uniform grid)
- Underwood roughness length – $z_0$
- Porosity – $\beta$
- Drag coefficients – $C1$ and $C2$
Concept of Porosity

- Given a generic volume occupied by fluid and solid phases, its porosity $\beta$ is defined as the ratio

$$\beta = \frac{\text{volume of fluid phases}}{\text{total volume}}$$
On the concept of Darcy’s velocity

- The Darcy’s velocity is the velocity that would occur if the whole volume was occupied by the fluid

\[ U_D = U \beta \]
Every element of the canopy introduces in the flow a sink of momentum

- So inside the canopy the momentum RANS equations present an additional term $S_j$

$$\rho U_i \frac{\partial U_j}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \mu_t \frac{\partial U_j}{\partial x_i} \right] - \frac{\partial P}{\partial x_j} + \rho f_j + S_j$$

$S_j \text{ [N/m}^3\]}

- Advection
- Diffusion

- Additional sources/sinks
- Body forces (gravity)
- Pressure gradient
The sinks of momentum depend upon porosity and velocity

- A classical approach (for high porous materials) is to consider the sinks of momentum proportional to the velocity.
- In the Darcy’s law the advective and diffusive terms are neglected, so the gravity

\[ S_U = C_V U \]

\[ C_V = \frac{\mu}{k} \]

\[ \vec{V} P = -C_V \vec{U}_D \]

Darcy’s law

\[ k = \frac{q \mu L}{A \Delta P} \]

Darcy’s law
Sinks of momentum implemented in WindSim 4.5

- Sinks of momentum \([N/m^3]\): two terms

\[
\vec{S} = -\rho C_1 \vec{U} - \rho C_2 |\vec{U}| \vec{U}
\]

Viscous force

Pressure force

Since the high Reynolds numbers

Pressure >> viscous forces
Present model

- In the canopy model of WindSim is possible to set the drag coefficients $C_1$ and $C_2$ where:
  - $C_1$ is the ratio of kinetic viscosity to permeability
  - $C_2$ is a drag coefficient multiplied by the ratio of total frontal area to volume

$$
[C_1] = \frac{1}{s} \quad [C_2] = \frac{1}{m} = \frac{m^2}{m^3}
$$

$$
C_1 = \frac{\mu}{\rho k} = \frac{\nu}{k}
$$

$k [m^2]$ permeability
How to estimate the porosity $k$?

- The relation $k$ vs. $\beta$ is proposed:

$$k = C \frac{\beta^2}{1 - \beta^2} \quad [m^2]$$

$$C = 0,0046215\,m^2$$

In this way it’s possible to estimate the value of the drag coefficient $C_1$ starting from a given value of porosity $\beta$. 

![Graph showing the relationship between porosity and permeability.](image)
As regards the porosity

Please visit the site:
http://www.sbe.hw.ac.uk/research/buildingeng/wind_modelling/gui_windbk.html

(Estimates of porosities obtained from 2d windbreaks)

<table>
<thead>
<tr>
<th>Species of tree</th>
<th>$\beta$ [%]</th>
<th>$k$ [m$^2$]</th>
<th>$C_1$ [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beech</td>
<td>84</td>
<td>1,108E-02</td>
<td>1,394E-03</td>
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<tr>
<td>Black cherry</td>
<td>77</td>
<td>6,731E-03</td>
<td>2,294E-03</td>
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<tr>
<td>Birch</td>
<td>55</td>
<td>2,004E-03</td>
<td>7,703E-03</td>
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<tr>
<td>Lime</td>
<td>54</td>
<td>1,902E-03</td>
<td>8,116E-03</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1,541E-03</td>
<td>1,002E-02</td>
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<tr>
<td>Ash</td>
<td>48</td>
<td>1,384E-03</td>
<td>1,116E-02</td>
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<tr>
<td>Mature maple</td>
<td>47</td>
<td>1,310E-03</td>
<td>1,178E-02</td>
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<tr>
<td>Scots pine</td>
<td>38</td>
<td>7,800E-04</td>
<td>1,980E-02</td>
</tr>
<tr>
<td>Firs</td>
<td>30</td>
<td>4,571E-04</td>
<td>3,378E-02</td>
</tr>
<tr>
<td>Spruce</td>
<td>29</td>
<td>4,244E-04</td>
<td>3,638E-02</td>
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<tr>
<td>Cypresses</td>
<td>15</td>
<td>1,064E-04</td>
<td>1,451E-01</td>
</tr>
<tr>
<td>Solid</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
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</table>
First test case: Step change in roughness (top view)

<table>
<thead>
<tr>
<th>Cells</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Tot.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>124</td>
<td>61</td>
<td>38</td>
<td>287432</td>
</tr>
</tbody>
</table>

(typical value for a forest)
The forest, 10 m height, has been discretized with 10 cells equally spaced.

### Vertical discretization

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
<th>Case D</th>
<th>Case E</th>
<th>Case F</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>15</td>
<td>50</td>
<td>84</td>
<td>15</td>
<td>50</td>
<td>84</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>0,1451</td>
<td>0,01002</td>
<td>0,001393</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,8535294</td>
<td>0,0055978</td>
<td>0,0004313</td>
</tr>
<tr>
<td>( u_{5m} )</td>
<td>0,17</td>
<td>1,79</td>
<td>3,23</td>
<td>0,15</td>
<td>1,73</td>
<td>3,21</td>
</tr>
<tr>
<td>( S )</td>
<td>2,93E-02</td>
<td>2,13E-02</td>
<td>5,35E-03</td>
<td>2,93E-02</td>
<td>2,13E-02</td>
<td>5,35E-03</td>
</tr>
</tbody>
</table>

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The forest, 10 m height, has been discretized with 10 cells equally spaced.
WT – Wind Tunnel
Moga 12 m forest
Uriarra 20 m forest
Bordeaux 13.5 m forest

Source Fig. 3.3 of:
Kaimal & Finnigan
Atmospheric Boundary Layer Flows
Oxford University Press
Conclusions

- With the proposed canopy model is possible to estimate properly the dissipation of momentum and the production of turbulence inside a forest
- Further validations are needed in order to state more precise guidelines for the choice of the parameters C1 and C2 used together
  - Masts inside forests (SgurrEnergy)
  - Wind farms close to forests