A Generalized Canopy Model for the Wind Prediction in the Forest and the Urban Area

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ABSTRACT

In this study, a generalize canopy model that can consider vegetation, buildings and porous obstacles is proposed. Flow field around two obstacles with different porosities are simulated. The results show a good agreement with the measurement. A wind tunnel test of the scale model of a city is also performed and simulated flow field by proposed mode was verified. The proposed model shows good agreement with the measurement.

KEYWORDS: CANOPY MODEL, WIND PREDICTION, URBAN AREA

Introduction

In order to predict the wind in the urban or dense forest area, canopy models, which consider the effect of the obstacles as external forces, have been proposed. However conventional urban canopy models have the disadvantage of inapplicability to the high packing density canopy. In the prediction of wind in urban area, grids with high packing density are often generated. In this study, a new general canopy model which can consider the effect of the vegetation and solid buildings simultaneously is proposed and verified by wind tunnel test and the onsite measurement.

Generalized canopy model

Basic equations

In this study, conservation of mass and momentum are solved numerically.

\[
\frac{\partial \overline{\rho u_i}}{\partial t} + \frac{\partial \overline{\rho \overline{u_i} u_j}}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \overline{u_i}}{\partial x_j} - \rho \overline{u_j u'_i} \right) + f_{ui}
\]  
(1)

where \( \overline{u_i} \) and \( u'_i \) are the mean and the fluctuating component of the apparent wind velocity and \( i \) denotes the direction. \( \overline{p} \) is the apparent pressure, \( \rho \) is the density of fluid, \( \mu \) is the molecular viscosity and \( F_{ui} \) is the fluid force per unit grid volume on obstacles which will be described in detail in the next section. The turbulence of flow is estimated by the Launder and Kato (1993) model.

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho \overline{u_i} u_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right) - \rho u_i u'_j \frac{\partial \overline{u_i}}{\partial x_j} - \rho \varepsilon + f_k
\]  
(2)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho \overline{u_j} \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right) - C_{\varepsilon 1} \frac{\varepsilon}{k} \rho u_i u'_j \frac{\partial \overline{u_i}}{\partial x_j} - C_{\varepsilon 2} \frac{\rho \varepsilon^2}{k} + f_\varepsilon
\]  
(3)

In these equations, physical variables are treated as apparent variables. The terms \( f_k \) and \( f_\varepsilon \) is the generation/dissipation of turbulence per unit grid volume within canopy layer described next section. Any apparent variables \( \phi \) averaged for whole grid volume is related with mean fluid property \( \tilde{\phi} \) averaged for fluid volume as below.

\[
\phi = \gamma_f \tilde{\phi}
\]  
(4)

where \( \gamma_f \) is the porosity defined as the ratio of the volume of the fluid to the total volume.
Generalization of external force

Fluid force on any bluff body is described with the drag coefficient $C_D$ and a reference area $A_o$, as

$$F_{u,i} = \frac{1}{2} \rho C_D A_o \sqrt{u_i^2 u^o_i}$$

(5)

Based on this equation, $f_{u,i}$ in equation (1) is derived as below.

$$f_{u,i} = \frac{F_{u,i}}{V_{grid}} = -\frac{1}{2} \rho C_f \gamma \frac{1}{l_o} \sqrt{u_i^2 u^o_i}, \quad C_f = \frac{C_D}{(1 - \gamma_o)^2}, \quad l_o = \frac{V_o}{A_o}$$

(6)

where $C_f$ is also a kind of the drag coefficient, $l_o$ is defined as the representative length scale of obstacles. In case of buildings whose cross section is square, $l_o$ corresponds to its depth and $A_o$ comes to be one of side walls of it. In case of building that has arbitrary shape of cross section, it is converted to the equivalent building that has square cross section. $V_{grid}$ is the volume of grid. $V_o$ is the volume of obstacles. $\gamma_o$ is called the packing density defined as $\gamma_o = 1 - \gamma_f$. According to empirical data for the drag coefficient $C_D$ of urban canopy obtained by Maruyama (1992), $C_D$ is a function of $\gamma_o$ and the maximum value is about 3.0, when the packing density is around 20% to 30% and it gradually decreases with increasing of $\gamma_o$. Considering those data, the drag coefficient $C_f$ is modeled like below for urban canopy.

$$C_f = \frac{1}{(1 - \gamma_o)^2} \min \left( \frac{1.63}{(1 - \gamma_o)^2} 3.0(1 - \gamma_o) \right)$$

(7)

In order to prevent numerical instability, the value of $\gamma_o$ is limited from 0 to 1-$\delta$. $\delta$ takes the constant value of $10^{-4}$. This additional term does not cause significant change in the flow field.

Firstly, the relation with the porous medium theory is described. The Burk-Plummer (1928) equation, in which the porous media is assumed to be spheres and the fluid force is estimated theoretically in turbulent flow, shown as

$$f_{u,i} = \frac{C \rho}{D} \frac{1 - \gamma_f}{\gamma_f^2} \sqrt{u_i^2 u^o_i}, \quad \bar{D} = \frac{C_S V_{porous}}{S_{porous}}$$

(8)

where $C$ is an empirical constant and usually 1.75 is chosen. $\bar{D}$ is the representative diameter of the porous media. $V_{porous}$ and $S_{porous}$ are the volume and the surface of the porous media respectively. The $C_S$ is called the shape parameter and depends on the aspect ratio of the porous media. In case of sphere or cube, the shape parameter becomes 6. If the porous media is sphere, $\bar{D}$ is equivalent to the diameter of the sphere. Comparison of equation (6) and equation (8) leads to equivalent conversion like,

$$C_f = \frac{4C}{3(1 - \gamma_o)^2}, \quad l_o = \frac{V_o}{A_o} = \frac{\pi}{6} \bar{D}^3 \left( \frac{\pi}{4} \bar{D}^2 \right)^{-1} = \frac{2\bar{D}}{3}$$

(9)

For the vegetation canopy model shown below is also described by equation (10).

$$f_{u,i} = -\frac{1}{2} \rho C_{D,t} a_t \sqrt{u_i^2 u^o_i}, \quad a_t = \frac{S_{leaf}}{V_{grid}}$$

(10)

where $C_{D,t}$ is drag coefficient of vegetation, $a_t$ is called the leaf area density. These parameters are obtained empirically. $S_{leaf}$ is a total leaf area in volume $V_{Grid}$. For vegetation, the equivalent conversion of parameters from vegetation canopy to equation (6) is shown as,

$$C_f = C_{D,t} \quad l_o = \frac{V_{leaf}}{S_{leaf}} = \frac{\gamma_o V_{grid}}{S_{leaf}} = \frac{\gamma_o}{a_t}$$

(11)

However in this case $\gamma_o$ can not be obtained explicitly, it comes to be canceled out with $1/\gamma_o$ in the equation (6). In this case, the representative length corresponds to the averaged thickness of leaves.

For the source terms for turbulent kinetic energy and its dissipation rate, Green’s model (1992) that considers the promoting process of energy cascade in canopy layer is adopted.

$$F_k = \beta_k \rho C_{f \gamma a} \frac{\varepsilon}{2 l_o k} \sqrt{u_i^2 u^o_i} \left( 1 - \frac{\beta_d}{\beta_k} k \right), \quad \varepsilon = C_{v1} \beta_k \rho C_{f \gamma a} \frac{\varepsilon}{2 l_o k} \sqrt{u_i^2 u^o_i} \left( 1 - \frac{C_{v2}}{C_{v1}} \beta_k \frac{k}{\sqrt{u_i^2 u^o_i}} \right)$$

(12)

where the model constants $\beta_k$, $C_{v1}$, $C_{v2}$ are set to 1.0, 1.5, 1.0 respectively. Although 4.0 is used for $\beta_d$, generally, $\beta_d$ should be the function of the packing density $\gamma_o$. In this study, the generation
and dissipation of the turbulence kinetic energy in the equation (12) assumed to be canceled out in high packing density region. Then next equation is obtained.

$$\beta_d = \left( \sqrt{\frac{\nu}{k}} \right)$$  

(13)

In this study, numerical simulations for high packing density (more than 0.5) are conducted to estimate the relationship between $\beta_d$ and $\gamma_o$ under the assumption of the equation (13). At last $\beta_d$ is modeled like,

$$\beta_d' = C_{m1} \exp\left( -\frac{1 - \gamma_o}{\gamma_o} \right) + C_{m2}$$  

(14)

Model parameters are identified and result to be $C_{m1} = 0.489$ and $C_{m2} = -0.4796$. Finally model parameter $\beta_d$ is introduced like

$$\beta_d = \min(4.0, \beta_d')$$  

(15)

As a consequent, any external force model can be described by the proposed model. In this sense, this model can be called “Generalized canopy model”.

**Verification by single obstacle**

Proposed canopy model was verified for two different obstacles with different densities.

The first obstacle is a pine tree with 7m height (Figure 1). The drag coefficient and leaf area density is 0.9 and 1.17 (m-1) respectively. The wind speed at the height of 1.5 $H$, 3.0 $H$, 4.5 $H$ and 6.0 $H$ were measured behind the tree by Kurotani et al. (2001) and compared with the simulation. Figure 3 shows the normalized wind speed profile behind the tree. The proposed canopy model shows a good agreement with the measurement.

The second model was a prism shown in Figure 2. The wind field was conducted by Ishihara and Hibi (1998). The simulation results are shown in Figure 4. The simulated flow field also shows good agreement with the measurement.

**Verification by an urban model**

In order to verify the proposed model for the flow around multiple obstacles, the proposed model was verified by a wind tunnel test with an urban model.

The computational domain is 10.3km(x) $\times$ 7.3km(y) $\times$ 1.5km(z) and the wind speed was measured at the center of the model. The minimum horizontal grid size is 30m at the center of the model and the minimum vertical grid size is 3.0m at the ground surface, which results in the total grid number of 194,000. At the inlet boundary,
measured vertical profile of the wind speed was given.

The shape, height and the position of the buildings in the city are decided by using a digital map “Zmap-TOWN2” issued by Zenrin Corporation. It contains vector outline and the number of floors of the building. The average floor height is assumed to be 3.5m. Figure 5(a) shows the digital map of the city near the center of the model and (b) shows the calculated plan area for each grid. Perimeter and average building heights are also calculated.

Figure 6 shows the wind speed ratio at the height of 13.5m. In addition to the wind tunnel test and the result of the proposed model is shown. The proposed canopy model shows agreement with the measurement.

Conclusions
In this study, a generalize canopy model that can consider different kind of obstacles (vegetation, buildings and porous obstacles) is proposed. Flow field around two obstacles with different porosities are simulated. The results show good agreements with the measurement. A wind tunnel test of the scale model of a city is also performed and simulated flow field by proposed mode was verified. The proposed model shows good agreement with the measurement.

Reference