A numerical tree canopy model and its application in computational wind engineering simulation

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ABSTRACT: Existing turbulence model had been improved by introducing additional source/sink terms in the governing equations to appropriately consider the effect of tree canopy on the wind environment flow. The new source term model $S_\omega$ for the turbulence frequency $\omega$ equation in the SST $k$-$\omega$ model was proposed and numerically verified through the simulation of the windbreak flow firstly. Then it was adopted in the wind environment optimal design of the twin high-rise buildings of CABR (China Academy of Building Research). With the new inflow boundary conditions developed in the previous studies, it was concluded that the theoretically reasonable source term model was applicable for modeling the tree canopy flow and could get relatively better results.

KEYWORDS: wind environment, numerical simulation, SST $k$-$\omega$ model, additional source/sink term, high-rise building, optimization design.

1. INTRODUCTION

In studies on wind environment around buildings, usually the influence of vegetation cover cannot be ignored. The windbreak formed by the vegetation cover increases the wind drag and subsequently reduces the downstream wind speed effectively. Vegetation cover and its influences on surface roughness have therefore induced considerable complexity to computational modeling of airflow.

For large-scale atmospheric flows, the broad characteristics of flow are concerned most, and the modified wall function considering roughness modification can be then used to model the near ground flow. From the viewpoint of numerical simulation, the wall function has substantially reduced the excessive grid requirement, particularly in the viscous sub-layer. It is however that this method is not suitable for modeling the near ground canopy flow since the use of roughness parameters in the modified law of the wall provides no information of the turbulence structure within the canopy region in terms of the vegetation-related parameters, such as leaf area density (LAD) [1].

In focusing on surface flow complexity, plant drag can be accounted for by incorporating surface roughness parameters and/or introducing additional source/sink terms [1-4]. As such, modified transport equations can be derived to establish mean momentum, turbulent kinetic energy and turbulent kinetic dissipation rate.

In this paper, a more appropriate source term $S_\omega$ in the $k$-$\omega$ model has been deduced through the theoretical analogy with the two turbulence models, i.e. the $k$-$\epsilon$ model and the $k$-$\omega$ model. The new source term $S_\omega$ for the SST $k$-$\omega$ model was numerically verified by comparing the numerical results with the mean velocity profiles at different downstream locations of the vegetated windbreak experiment conducted by Kurotani et al. (2002) [5]. At last, the proposed source term model was adopted in the wind environment optimal design of the twin high-rise buildings of China Academy of Building Research (CABR). The effects of tree canopy on the wind flow in the passage formed by the two closely arranged buildings
was numerically investigated and then compared with the situation without the tree canopy. In the numerical simulations, the new inflow boundary conditions proposed by Yang et al. (2008, 2009, 2012) \cite{6-8} are used to model the equilibrium ABL. By using this new inflow boundary condition profiles, the stream-wise errors can be significantly reduced if a good fit between the inflow profiles and the model was used \cite{9}. Based on the results of the numerical simulation, technical measures to ameliorate the unfavorable wind environment were then suggested.

2. TURBULENCE MODELS AND ADDITIONAL SOURCE/SINK TERMS

2.1 k-\(\omega\) model

For the k-\(\omega\) model \cite{10}, the governing equations for the turbulent kinetic energy \(k\) and turbulence frequency \(\omega\) can be expressed as follows:

\[
\frac{\partial k}{\partial t} + \frac{\partial u_i k}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \nu_t \frac{\partial k}{\partial x_j} \right) + P_k - Y_k + S_k
\]

(1)

\[
\frac{\partial \omega}{\partial t} + \frac{\partial u_i \omega}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{\nu_t}{\sigma_\omega} \frac{\partial \omega}{\partial x_j} \right) + P_\omega - Y_\omega + S_\omega
\]

(2)

where \(P_k\) and \(P_\omega\) represents the production terms of \(k\) and \(\omega\), and \(Y_k\) and \(Y_\omega\) are the effective dissipation terms due to turbulence. The \(S_k\) and \(S_\omega\) are the additional source/sink terms of the \(k\) and \(\omega\) transport equations, respectively. The turbulent viscosity is computed by combining \(k\) and \(\omega\) as follows:

\[
\nu_t = \frac{k}{\omega}
\]

(3)

2.2 Additional source/sink terms model of the SST k-\(\omega\) model

The k-\(\omega\) based SST model developed by Menter (1994) \cite{10} employs the k-\(\omega\) model near the surface and the k-\(\varepsilon\) model in the free-shear layers. A blending function is adopted to bridge these two models. The SST k-\(\omega\) model takes into account of the transport of the turbulent shear stress and gives accurate predictions of the onset and the amount of flow separation under adverse pressure gradients \cite{10}. In view of its relatively high efficiency for numerical simulation and accurate solution, the SST k-\(\omega\) model was adopted in this study.

The plant effects were accounted for by introducing the additional source/sink terms in the mean momentum, the turbulence kinetic energy \(k\) and turbulence frequency \(\omega\) equations in the SST k-\(\omega\) model, which is more suitable for blunt body flow, compared with the standard k-\(\varepsilon\) model \cite{6}. The expressions of the additional source/sink terms have been proposed by a number of researchers \cite{2-4}. Mochida et al. (2006) \cite{10} conducted a numerical study and compared the performances of different forms of additional source/sink terms on the tree canopy flow.

For the k-\(\varepsilon\) model, the source/sink terms accounting for the plant drag are expressed as follows \cite{12}:

\[
S_{ui} = -C_d A u_i U
\]

(4)
In Eqs. (4)-(6), $C_d$ is the drag coefficient; $A$ is the leaf area density (LAD) ($m^2 m^{-3}$); $u_i$ is the velocity component of $i$ direction; where $U=|u_i u_i|^{1/2}$ is the absolute value of the spatially averaged wind speed. $\beta_p$ was the fraction of mean flow kinetic energy being converted to wake-generated energy by canopy drag, and $\beta_d$ was the magnitude of energy losses from interactions with obstacles. For the standard $k$-$\varepsilon$ model, the typical values of $\beta_p$ and $\beta_d$ are 1 and 4, respectively. $\alpha_p$ and $\alpha_d$ are the adjustable model constants, and the analytical values are both 1.5. For the SST $k$-$\omega$ model, the values of $\alpha_p$ and $\alpha_d$ are modified to 3.2 and 0, respectively.

Due to the relationship between the SST $k$-$\omega$ model and the standard $k$-$\varepsilon$ model, the source/sink terms of the mean momentum and $k$ equations in the standard $k$-$\varepsilon$ model, i.e. Eqs. (4) and (5), can be adopted in the SST $k$-$\omega$ model directly. While, for the source/sink term of the $\omega$ equation, almost no theoretical expression can be referred to directly. For example, Pattanapol et al. (2008) adopted the equation of $S_\varepsilon$ as the form of the expression of $S_\omega$, directly only through a simple linear transformation between $\varepsilon$ and $\omega$.

Theoretical derivation had been conducted to obtain a reasonable source term $S_\omega$ as Eq.(7).

$$S_\omega = C_d A(\alpha_p - 1) \beta_p \frac{\omega}{k} U^3 - C_d A(\alpha_d - 1) \beta_d \frac{\omega}{k} U_k$$

The newly-derived source term $S_\omega$ of Eq. (7), which was deduced from the turbulence model equations, will be employed along with the source/sink terms of $S_u$ and $S_k$ in the numerical simulation of windbreak flow in the next section.

3. NUMERICAL VERIFICATION

3.1 Model Setup

Kurotani et al. (2002) performed a field experiment of vegetated windbreak flow and the experimental results are available in the website (http://www.aij.or.jp/). Based on the experimental results, Mochida et al. (2006) carried out a series of parameter optimization studies on the additional source/sink terms of $k$-$\varepsilon$ model.

The experiment and the numerical simulations conducted by Mochida et al. (2006) were referred to, and a corresponding 2D numerical model was built. The dimensions of the rectangular computational domain were 100m(L)$\times$100m(W), which could be referred to Franke et al. (2007). The domain was discretized by structural grids and the finest mesh grid close to the ground was set as 0.1 m. The total amount of cells was 50,000. The present work was conducted using the CFD code Fluent 6.3 (Fluent Inc.). The effect of tree canopy on the wind flow was modeled by adding the source/sink terms of $S_u$, $S_k$ and $S_\omega$ (i.e. Eqs. (4), (5) and (7)) into the momentum, $k$ and $\omega$ equations, respectively, using the user defined functions (UDF). The flow was assumed incompressible and steady, and the SIMPLE algorithm was used for pressure-velocity coupling. The second order upwind difference scheme, QUICK, was adopted for all the convective terms in the momentum equation and turbulence model equations. The diffusive terms were discretized by second order central difference scheme. The flow field was initiated by the inlet boundary condition. The
convergence criteria of the scaled residuals for all variables and the continuity equation were set as $10^{-4}$. To obtain convergent results, although the convergence criteria were achieved, additional iterations were performed to ensure a stable convergence over a sufficient period.

The numerical simulations on different mesh resolutions were performed at the onset to check the requirement of mesh independence. Four variations of mesh densities, which was similar to that was adopted in Yang et al. (2009) [7], were investigated. It was concluded that the CFD simulation results under the present settings were independent of the mesh resolution. The mean velocity profiles obtained from the current numerical simulation at different locations downstream of the vegetated windbreak were compared with the experimental data [5] and acceptable results have been obtained [15].

3.2 Modeling of equilibrium atmospheric boundary layer

The modeling of equilibrium atmospheric boundary layer (ABL) was an important precondition for a proper numerical simulation of flows around buildings [17]. The most important requirement of equilibrium ABLs was the horizontal homogeneity, which means that the stream-wise gradients of all variables should be zero.

The issue of generating an equilibrium ABL was investigated from the viewpoint of the turbulence model. The approximate solution to the standard k-ε model was derived based on the assumption of the local equilibrium of turbulence, and then a new set of inflow turbulence boundary conditions for modeling equilibrium ABL was proposed [6][7]. The application of the new inflow boundary conditions was further extended to the SST k-ω model for modeling equilibrium ABL [8]. The performance and applicability of this new set of inflow boundary condition have been recently validated [9][18], and it has been adopted in the numerical simulations of ABL transport phenomena [19][21].

The first step of the numerical verification was the simulation of simple boundary layer flow in an empty domain to confirm whether the equilibrium ABL is adequately generated. The boundary conditions of the numerical model were stipulated in Table 1. The parameters in the inflow boundary conditions were referred to the experiment of Kurotani et al. (2002) and the numerical simulations by Mochida et al. (2006) [11], in which $u=5.6\text{m/s}$, $H_b=9\text{m}$, $\alpha=0.22$, $D_1=-8.94\text{m}^4/\text{s}^4$, $D_2=53.4\text{ m}^4/\text{s}^4$.

Numerical simulation shows that both the mean velocity and turbulent kinetic energy profiles were sustained satisfactorily throughout the whole domain under the present inflow turbulence boundary conditions [7][15].

<table>
<thead>
<tr>
<th>Location of computational domain</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow face</td>
<td>Defining the mean velocity ($u$), TKE ($k$) and turbulence frequency ($\omega$)</td>
</tr>
<tr>
<td></td>
<td>$u = u_c(z/H_b)^\alpha$, $v = 0$, $w = 0$; $k = \sqrt{D_1 \alpha^{\alpha} + D_2}$, $\omega = \varepsilon / (C_\mu k)$;</td>
</tr>
<tr>
<td></td>
<td>where $\varepsilon = \alpha C_\mu^2 (u/z) \sqrt{D_1 \alpha^{\alpha} + D_1}$</td>
</tr>
<tr>
<td>Outflow face</td>
<td>Fully developed outflow</td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial}{\partial x}(u,v,w,k,\omega) = 0$</td>
</tr>
<tr>
<td>Upper face of computational domain</td>
<td>Free slip</td>
</tr>
<tr>
<td></td>
<td>$w = 0$, $\frac{\partial}{\partial y}(u,v,k,\omega) = 0$</td>
</tr>
<tr>
<td>Side faces of computational domain</td>
<td>Free slip</td>
</tr>
<tr>
<td></td>
<td>$v = 0$, $\frac{\partial}{\partial y}(u,w,k,\omega) = 0$</td>
</tr>
<tr>
<td>Ground surface boundary wall</td>
<td>No slip wall with wall roughness modification, roughness height $K_s=0.05m$ and roughness constant $C_s=0.5$</td>
</tr>
</tbody>
</table>

Table 1. Boundary conditions of the numerical model
4. APPLICATION

4.1 Introduction

The assessment and modification research of wind environment of the high-rise buildings Silvertop Towers had been reported by Blocken et al. (2004)\textsuperscript{22}. CFD simulation was demonstrated being an effective method for such assessment \textsuperscript{23}. The method of introducing the additional source/sink terms in governing equations to appropriately consider the tree canopy effect are further applied to the wind environment optimization of the high-rise buildings of China Academy of Building Research (CABR).

The new mansion of CABR (i.e. the left building in Figure 1) was built close to the existing building, and both were 80m in height (h). Due to the limited site area, the minimum width of the passage, b\textsubscript{min}, is only about 15m. Therefore, the ratio of b\textsubscript{min}/h was as small as 0.19. This narrow passage formed by two closely arranged high-rise buildings will be the main entrance of CABR in the future.

Due to lack of obstacles in front of the buildings, moreover, the passage being towards the local dominant wind direction in the whole year, therefore, the pedestrian wind environment was deteriorated in windy days for the wind speed in the passage being accelerated apparently. In order to quantitatively evaluate the pedestrian wind environment comfort and safety around the buildings, particularly at the narrow passage, a detailed wind tunnel test and numerical simulations had been carried out.

According to the wind tunnel test and the numerical simulations, the maximum wind speed ratio C\textsubscript{u}, which was defined as the ratio of the local mean wind speed U\textsubscript{p} to the undisturbed wind speed U\textsubscript{f} at the pedestrian level., i.e., C\textsubscript{u}=U\textsubscript{p}/U\textsubscript{f}, could reach 1.8. Combining with the local wind climate statistic data, it resulted that the peak wind speed was as high as the Beaufort scale 8. The probability of occurrence of such high wind speed in the passage was estimated to be nearly 8 times per year. That implied the wind environment in the passage does not satisfy the basic requirements of safety and comfort for pedestrians.

4.2 Wind environment optimization design

In order to ameliorate the unfavorable wind environment, additional optimization scheme in cooperation with architects have been performed. Some remedial measures were suggested, for example, a large billboard as high as 9m was planned to set up in front of the windward opening of the passage as a windbreak, and the semi-opened corridor on the ground floor of the new mansion was recommended to be closed and used as pedestrian pathway, as depicted in Figure 2.

Though the proposed measures can potentially ameliorate the high wind speed environment at some extent, further numerical simulation (numerical model see Figure 3)
showed that the wind speed at the pedestrian level still tended to unfavorable. This is because
the major characteristic of the narrow passage formed by the two high-rise buildings largely
remains unchanged.

For example, the big billboard can successfully block off strong wind from north in the
downstream near field but the flow separated over the billboard was speeding up and
reattaching farther downstream, as reported in Figure 4. Therefore the high wind speed
environment in the southern end of the passage was not mitigated and may even be worse in
some situations as demonstrated here. Consequently, optimizing the quality of the wind
environment around the building, in particular the passage was challenging for wind
engineers.

Figure 3. Grid discretization of the
numerical model of CABR buildings

Figure 4. The wind flow streamlines around the building under the
north wind

4.3 Application of the tree canopy in the optimization design

4.3.1 Numerical model

The idea of installing tree canopy in the passage acting as a “soft” windbreak was then
proposed and the numerical simulation was carried out. The full scale 3D model of CABR
buildings was built according to the architectural design. Some unnecessary architectural
details and features were simplified to avoid over-weighted calculation load. The dimensions
of the computational domain were set as 720m x 1360m x 560m (i.e. W x L x H), resulting in
the blockage ratio of the domain being smaller than 3%.

The grid discretization scheme was designed to achieve a balance between the precision of
numerical results and the computational time. The whole domain was divided into two parts
as showed in Figure 3 and then hexahedron cells were adopted for both internal and external
parts’ discretization. The size of the smallest cells close to the building boundaries in the
internal part was approximately 0.5m. This scheme gives the total grid cells of about 2
million.

The boundary conditions were set following the expressions in Tab.1, while the two
constants of $k$, $D_1$ and $D_2$ were changed slightly in consideration of the local wind terrain
feature. Here they were defined as: $D_1=-8.93m^{-\alpha} s^4$, $D_2=53.1 m^4/s^4$; where $\alpha=0.22$.

In the numerical model, a line of tree canopy was set in the middle of the passage, as
illustrated in Figure 5(b). The dimensions of the tree model were 50.0m(L) x 1.0m(W)
 x 1.5m(H). The drag coefficient $C_d$ and LAD of the tree model were 0.8 and 1.17m$^2$/m$^3$,
respectively. The details of the tree windbreak can be referred to the paper of Kurotani et al.
(2002)[5].

4.3.2 Calculation results

Figure 5 illustrates the comparisons of the wind velocity ratios $C_u$ at the pedestrian level
before and after setting up the vegetated windbreak in the center of the passage subject to the north wind. It can be clearly seen from the figure that the high wind velocity ratio (i.e. $C_u > 1.5$) was restrained and the area with high wind velocities, especially in the southern part of passage, was reduced significantly after the tree canopy was “planted” (Figure 5 (b)). Therefore, it could partly overcome the negative influence brought by the installation of the windbreak at the northern end as showed in Figure 4.

Numerical simulations exhibited the effects of the tree canopy partly eliminating the unfavorable strong pedestrian wind and improving the wind environment in the passage. Based on the numerical results, a proposal of ameliorating the wind environment of this development project was presented. A line of tree canopy in the middle of the passage with properly designed windbreak facilities installed at the northern end of the passage can effectively reduce the high wind speed and avoid the unfavorable wind environment.

5. CONCLUSIONS

Existing turbulence model has been improved in order to appropriately consider the effect of tree canopy on the wind environment flow, which is realized by introducing additional source/sink terms in the governing equations. The new source term model $S_{\omega}$ for the turbulence frequency $\omega$ equation in the SST $k-\omega$ model was derived through the theoretical analogy. Its applicability and performance were numerically verified by performing the simulation of the windbreak flow. Then the proposed source term model was adopted in the wind environment optimal design of the twin high-rise buildings of CABR.

Using the new inflow boundary conditions developed in the previous study to model the equilibrium atmospheric boundary layer, it was concluded that the theoretically reasonable source/sink term model of the SST $k-\omega$ model was applicable for the modeling of tree canopy flow. Though some optimization works of the parameters in the model have been performed to achieve better results, the authors believe that more refined study will be helpful for further improving the numerical accuracy.

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7. REFERENCES


