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Numerical study of turbulent flow fields around of a row of trees and an isolated building by using modified k-ε model and LES model

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A R T I C L E I N F O

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A B S T R A C T

Turbulent flow fields over two typical urban elements, a row of trees with low packing density and an isolated building with high packing density, are investigated by a modified $k-\varepsilon$ model and a LES model. The applicability of these two models is evaluated by the validation metrics. Instantaneous flow fields are visualized by vortex cores and examined by quadrant analysis. In the wake region of the row of trees, predicted mean wind speed by the modified $k-\varepsilon$ model shows favourable agreement with the measured data, but turbulent kinetic energy is underestimated since the modified $k-\varepsilon$ model is not capable of simulating organized motions. In the wake region of the isolated building, both predicted mean wind speed and turbulent kinetic energy by the modified $k-\varepsilon$ model are slightly underestimated due to lack of the vortex shedding in the simulation. On the other hand, LES model well predicts both mean wind speed and turbulent kinetic energy since all large vortices are directly resolved by LES model.

1. Introduction

With increasing requirement on renewable energy, wind turbines are installed in or near the urban and suburban areas, where the local wind condition is strongly affected by surrounding trees and buildings. Prediction of mean wind speed and turbulence are important, because mean wind speed is directly related to potential wind energy, while turbulence results in fluctuating wind load on the structure components and affects the fatigue life of wind turbine. Therefore, accurate prediction of turbulent flow fields around trees and buildings is necessary not only for designing of wind turbine but also for maintenance of wind turbines (IEC 61400-2, 2006).

With the aim of providing accurate prediction of turbulent flow field in the urban area, modelling of the effect of surface roughness is a key factor. Surface roughness trees and buildings are dominant and modelling them is necessary. As to modelling buildings, the rigid wall approach was applied by many researches (Gousseau et al. (2011), Blocken et al. (2012), Philips et al. (2013) and Cheng and Porte-Agel (Cheng and Porté-Agel, 2015), Mochida et al. (2002), Tominaga et al. (2008) and Gousseau et al. (2013)), in which detailed geometry information of each building are used and wall functions are applied for the boundary condition of building surface. However, this approach requires large effort on grid generation and calculation, and its application is therefore limited to a small area. On modelling vegetation, the canopy model is the only choice, which considers the fluid force and, turbulence generation and dissipation due to obstacles by introducing source terms into the momentum equation and turbulence transportation equations. Researches on canopy model with Reynolds average turbulence model (RANS) for vegetation and unban canopies have been carried out by Wilson (1988), Green (1992), Liu et al. (1996), Aumond et al. (2013), Suzuki et al. (2002) and Iwata et al. (2004), Maruyama (1993), Salim et al. (2015). However, conventional canopy models have a limitation that they can only be applicable to the canopy with a low packing density. Moreover, Mochida et al. (2008) provided a detailed comparison of various RANS models for the simulation of the wind flow through the row of trees, but the organized motions around them and the reason of discrepancies between predicted and measured turbulent flow fields should be further demonstrated. Enoki et al. (2009) and Enoki and Ishihara (2012) proposed a generalized canopy model which is able to consider the effect of the vegetation and buildings simultaneously. The generalized canopy model together with a modified $k-\varepsilon$ model has been applied for wind prediction of a single building as well as a real urban area. Comparing with rigid wall approach, the canopy model relax the requirement of geometry in the region close to obstacles, and it allows less computational grid. Furthermore, a simple grid system can be used in any size of urban areas. However, there are still some discrepancies

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between predicted and measured flow field and the reasons should be investigated. Moreover, accuracy of the LES model with the generalized canopy model has not been evaluated yet.

LES models are also used with rigid wall approach to predict unsteady flow fields over buildings (Rodi (1997), Yoshie et al., 2007, 2011 and Xie and Castro (2006)). They attributed the good performance of LES model to predict periodic vortex shedding and highlighted the importance of inflow turbulence on the accuracy of simulation using LES model. On modelling trees, some efforts were also made by using LES model (Yang et al. (2006), Bailey and Stoll (2013), Mueller et al. (2014) and Lopes et al. (2013)). However, accurate prediction with LES model depends on several issues, such as turbulent inflow condition and grid resolution. Therefore, a comparison between RANS and LES models for canopy flows with low and high packing densities is necessary to clarify the applicability of each turbulence model.

In this study, the numerical methods are given in section 2, including governing equations, fluid force and turbulence models, boundary condition and numerical schemes used in the simulations, as well as analysis methods applied in the discussion. In section 3, two typical urban elements are discussed. At first, the experiment in each case is briefly described, then turbulent flow fields are investigated and applicability of these two models is evaluated by the validation metrics. Instantaneous flow fields are visualized by vortex cores and examined by the quadrant analysis. Finally, conclusions are shown in section 4 based on above discussions.

2. Numerical method

2.1. Governing equations

For the analysis of the flow field with obstacles inside, two different approaches are used. The governing equations are constructed for the fluid part only in one approach, and for the flow field averaged over the computational grid in the other approach. In this study, the latter approach is used. The averaged continuity and momentum equations for incompressible flow with considering the effect of the buildings and vegetation are given by:

$$\frac{\partial(\rho\overline{u}_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho\overline{u}_i)}{\partial t} + \frac{\partial\left(\rho\overline{u}_j\overline{u}_i\right)}{\partial x_j} = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\overline{u}_i}{\partial x_j} + \frac{\partial\overline{u}_j}{\partial x_i}\right)\right] + \frac{\partial\tau_{ij}}{\partial x_j} + f_{\overline{u},i} \tag{2}$$

where $\overline{u}_i$ is the wind velocity in the ith direction ($u_1 = u$, $u_2 = v$ *and* $u_3 = w$). $\overline{p}$ is pressure, ρ is density of the fluid, μ is the molecular viscosity and $f_{\overline{u},i}$ is the fluid force per unit grid volume due to obstacles which is described in section 2.2. The overbar indicates time averaged mean value in the simulation with the modified $k-\varepsilon$ model, while it indicates the resolved value in the simulation with LES model. τ_{ij} is introduced to consider difference between $\overline{u_iu_j}$ and $\overline{u}_i\overline{u}_j$, i.e.,

$$\tau_{ij} = -\rho\left(\overline{u_iu_j} - \overline{u}_i\overline{u}_j\right) \tag{3}$$

Although the expression of τ_{ij} in Eq. (3) is the same for the modified $k-\varepsilon$ model and the LES model, its meaning is different in the two models. τ_{ij} in the modified $k-\varepsilon$ model is time-averaged Reynolds stress and stands for effect from vortex to mean flow field, while τ_{ij} in LES indicates the subgrid-scale Reynolds stress and accounts for contribution from unresolved smaller vortex to large size vortex.

2.2. Fuid force model

The generalized canopy model derived by Enoki and Ishihara (2012) is applied in this study and the fluid force in the momentum equations is:

Table 1
Parameters in the conventional and the generalized canopy models.

Type of obstacles	Conventional canopy model	Generalized canopy model
Vegetation (Wilson, 1988)	$f_{\overline{u},i} = -\frac{1}{2}\rho C_{D,t}a_t\lvert\overline{u}\rvert\overline{u}_i$	$C_f = C_{D,t}$ $\gamma_0 = a_tl_0$ $l_0 = 10^{-3}(m)$
Buildings (Maruyama, 1993)	$f_{\overline{u},i} = -\frac{1}{2}\rho C_{D,b}a_b\lvert\overline{u}\rvert\overline{u}_i$ $\gamma_b = V_b/V_{grid}$ $a_b = \frac{S_b}{4(1-\gamma_b)V_{grid}}$	$C_f = C_{D,b}/(1-\gamma_b)^3 = \frac{1}{(1-\gamma_b)^3}min\left[\frac{1.53}{1-\gamma_b}, 2.75(1-\gamma_b)\right]$ $\gamma_0 = \gamma_b$ $l_0 = 4V_b/S_b\ (m)$

$$f_{\overline{u},i} = -\frac{F_{\overline{u},i}}{V_{grid}} = -\frac{1}{2}\rho C_f\frac{\gamma_0}{l_0}\lvert\overline{u}\rvert\overline{u}_i \tag{4}$$

where, $f_{\overline{u},i}$ is the fluid force in the volume of grid, V_{grid}. $\lvert\overline{u}\rvert$ is the absolute value of mean wind speed per unit volume, C_f is the equivalent drag coefficient, l_0 is defined as the representative length scale of obstacles and γ_0 is the packing density. Canopy parameters for vegetation and buildings are summarized in Table 1, where $C_{D,t}$ and a_t are the drag coefficient and the leaf area density of vegetation respectively, $C_{D,b}$, V_b and S_b are the drag coefficient, the total volume and the total side surface of buildings.

2.3. Turbulence model

For the closure of the governing equations, τ_{ij} has to be modelled. In the modified $k-\varepsilon$ model, τ_{ij} is approximated by the linear turbulence viscosity model, i.e.,

$$\tau_{ij} = -\rho\overline{u'_iu'_j} = 2\mu_t\overline{S}_{ij} - \frac{2}{3}\rho k\delta_{ij} \tag{5}$$

where δ_{ij} is the Kronecker delta. Turbulence viscosity μ_t and rate-of-strain tensor $\overline{S}_{ij}$ are expressed as:

$$\mu_t = C_\mu\rho\frac{\overline{k}^2}{\overline{\varepsilon}} \tag{6}$$

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial\overline{u}_i}{\partial x_j} + \frac{\partial\overline{u}_j}{\partial x_i}\right) \tag{7}$$

In the modified $k-\varepsilon$ model, two additional equations are used to calculate the turbulent kinetic energy, k, and the dissipation rate, ε.

$$\frac{\partial\rho\overline{k}}{\partial t} + \frac{\partial\rho\overline{u}_j\overline{k}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial\overline{k}}{\partial x_j}\right] - \left[\frac{2}{3}\rho\overline{k}\delta_{ij}\frac{\partial\overline{u}_i}{\partial x_j} - P_k\right] - \rho\overline{\varepsilon} + f_k \tag{8}$$

$$\frac{\partial\rho\overline{\varepsilon}}{\partial t} + \frac{\partial\rho\overline{u}_j\overline{\varepsilon}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\overline{\varepsilon}}{\partial x_j}\right] - C_{\varepsilon1}\frac{\overline{\varepsilon}}{\overline{k}}\left[\frac{2}{3}\rho\overline{k}\delta_{ij}\frac{\partial\overline{u}_i}{\partial x_j} - P_k\right] - C_{\varepsilon2}\frac{\rho\overline{\varepsilon}^2}{\overline{k}} + f_\varepsilon \tag{9}$$

Parameters in the above equations are the same as those used in the standard $k-\varepsilon$ model, i.e., $C_\mu = 0.09$, $\sigma_k = 1.0$, $C_\varepsilon = 1.3$, $C_{\varepsilon1} = 1.44$ and $C_{\varepsilon2} = 1.92$. In order to settle overestimation of turbulent kinetic energy at stagnation point, turbulence source term P_k is estimated by Kato and Launder model (Kato, 1993). The source terms for turbulent kinetic energy and its dissipation rate are introduced to consider the promoting process of energy cascade in canopy layer. The model proposed by Enoki and Ishihara (Enoki et al., 2009; Enoki and Ishihara, 2012) is adopted and can be expressed as:

$$f_k = \frac{1}{2}\beta_p\rho C_fa\lvert\overline{u}\rvert^3 - \frac{1}{2}\beta_d\rho C_fa\lvert\overline{u}\rvert\overline{k} \tag{10}$$