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Evaluation of k-ε Reynolds stress modeling in an idealized urban canyon using LES

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ABSTRACT

In this study, a large-eddy simulation (LES) was conducted to investigate the validity of the modeling of Reynolds stress in standard k-ε model (k-ε model) for urban canyon flow. It was confirmed that the LES was more reliable than the k-ε model for urban canyon flow, through a comparison of experimental results. The k-ε model failed to reproduce the spatial distribution of the mean velocity within the urban canyon. It underestimated the absolute value of Reynolds stress $\langle u_1'u_3' \rangle$ and eddy viscosity coefficient ν_t, when compared to the LES. On the leeward side of the urban canyon, ν_t obtained by the LES was negative and the counter gradient diffusion was seen to occur. The budget of $\langle u_1'u_3' \rangle$ transport equation was analyzed using the results of the LES. At the top of the urban canyon and within it, the convection and diffusion terms showed an increase when compared to the production and pressure strain correlation terms. The gradient diffusion approximation of $\langle u_1'u_3' \rangle$ was not valid because the local equilibrium of $\langle u_1'u_3' \rangle$ transport equation was not correct. It was found necessary to incorporate the effect of the convection and diffusion terms in the modeling of $\langle u_1'u_3' \rangle$ for urban canyon flow.

1. Introduction

Urban environmental problems such as urban heat islands and air pollution have become serious. In a weak wind region like an urban canopy, heat and contaminants tend to stagnate, which makes urban environmental problems more serious. Improvement in computer performance has made it easier to assess urban environmental problems using computational fluid dynamics (CFD) analysis (Stathopoulos and Baskaran, 1996; Stathopoulos, 1997; Meroney et al., 1999; Murakami et al., 1999; Li et al., 2006; Baker, 2007; Mochida and Lun, 2008; Tominaga and Stathopoulos, 2013; Blocken, 2014; Blocken et al., 2016). Reynolds-averaged Navier–Stokes equations (RANS) models are widely used to model turbulence in CFD analyses for urban environmental assessment (Li et al., 2006; Tominaga and Stathopoulos, 2013; Blocken, 2014; Blocken et al., 2016). It is known that large-eddy simulation (LES) is more accurate than RANS for various types of flow fields because LES is able to capture large-scale unsteady motions such as building wakes which have different features according to flow field. However, the calculation load of LES is much larger than it is for RANS models, and thus LES is rarely used for practical applications.

European Cooperation in the field of Scientific and Technical Research (COST) Action C14 (Franke, 2006) and COST Action 732 (Franke et al., 2007; Schatzmann et al., 2010) have created the guideline of CFD analysis for urban air pollution assessment. In COST C14 and COST 732, the prediction accuracy of RANS models for flow and concentration fields was investigated by comparing to wind tunnel experiments. Moreover, they introduced the quality assessment criteria of CFD models using various types of validation metrics. Architectural Institute of Japan (AIJ) has also created the guideline for the practical use of CFD analysis based on RANS models for wind environmental assessment (Tominaga et al., 2008; Architectural Institute of Japan, 2016). In AIJ guideline, it is pointed out that in a weak wind region, such as behind high-rise buildings and within an urban canopy, the prediction accuracy of various types of RANS models decreases. It is surmised that this is because RANS models cannot reproduce large-scale unsteady motions in a wake region. However, RANS models are accurate enough in a strong wind region, such as the front and side of high-rise buildings, by applying modified turbulence models such as the Launder–Kato type k-ε model (Launder and Kato, 1993), renormalization group (RNG) k-ε model (Yakhot and Orszag, 1986; Yakhot et al., 1992), and so on. It is necessary to improve the prediction accuracy of RANS models in a weak wind region to promote the application of CFD analysis for assessment of urban environmental problems.

In many studies, the prediction accuracy of RANS models for urban

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flow has been evaluated through a comparison with results of wind tunnel experiments (Tominaga et al., 2004; Yoshie et al., 2007; Hertwig et al., 2012). However, in wind tunnel experiments, it is difficult to obtain the spatial distribution of the detailed turbulent statistics that are needed to investigate the modeling of Reynolds stress based on the momentum transfer mechanism, even though the modeling of Reynolds stress has a significant influence on the prediction accuracy of RANS models. In several studies, a database of turbulent statistics for various types of flow fields was created using the direct numerical simulation (DNS) or LES, to evaluate the prediction accuracy of the RANS models, and to investigate the modeling of Reynolds stress in detail. Hattori and Nagano (2004) used the DNS database that was created for channel flow (Kasagi et al., 1992; Nishimura and Kasagi, 1996; Moser et al., 1999) to investigate the modeling of Reynolds stress. Using the DNS database, they investigated the detailed turbulent structure near the wall of channel flow and proposed a new turbulence model, which took the wall-limiting behavior of the normal stress into account. They succeeded in predicting the anisotropy of the normal stress components near the wall, and improved the prediction accuracy of the RANS models. Nakanishi (2001), Nakanishi and Niino (2004a,b, 2009) conducted the LES for atmospheric boundary layer flow and used the LES result as reference data instead of field measurement data to investigate the flow structure in detail. They mainly modified the modeling of the turbulent length scale to consider the effect of atmospheric stability, and succeeded in overcoming weaknesses, for example insufficient growth of the convective boundary layer, of the conventional turbulence model. Murakami et al. (1990), Murakami (1993), and Rodi (1993, 1997) compared the results of LES and RANS analyses for flow around a bluff body with that of the wind tunnel experiment, and indicated that the LES was closer to the wind tunnel experiment than the RANS models. Moreover, using the results of the LES, they illustrated the characteristics of the complex flow structure around the bluff body and pointed out the problem of modeling of Reynolds stress in various types of RANS models.

Rossi and Iaccarino (2009, 2013), Rossi et al. (2010), Gousseau et al. (2011a,b, 2012) investigated the modeling of turbulent scalar flux using DNS or LES database. Rossi and Iaccarino (2009, 2013), Rossi et al. (2010) conducted the DNS and RANS analyses for pollutant dispersion around a bluff body. They pointed out the defect of the gradient diffusion approximation of turbulent scalar flux in RANS models using DNS database. It was found that the generalized gradient diffusion hypothesis (GGDH) (Daly and Harlow, 1970) and high-order gradient diffusion hypothesis (HOGGDH) (Abe and Suga, 2001) improved the prediction accuracy of RANS models. Gousseau et al. (2011a,b, 2012) also conducted the LES and RANS analyses for pollutant dispersion around a bluff body. They indicated that the convective scalar flux more contributed to the scalar transfer than the turbulent scalar flux and it is necessary to improve the prediction accuracy of the flow field and convective scalar flux for pollutant dispersion.

In several studies, the results of the LES and RANS analyses for urban canyon flow have been compared to those of wind tunnel experiments, or field measurements (Cheng et al., 2003; Xie and Castro, 2006; Santiago et al., 2010; Dejoan et al., 2010). The studies indicated that the LES was more accurate than the RANS models. Tominaga and Stathopoulos (2012) conducted the LES for urban canyon flow and used the result as the reference database to evaluate the prediction accuracy of the RANS models. They estimated the eddy viscosity coefficient using the results of the LES, and compared it to that obtained by the RNG k-ε model. It was revealed that the RNG k-ε model underestimated the eddy viscosity coefficient and could not simulate the turbulent momentum transfer sufficiently within the urban canyon. Coceal et al. (2006, 2007), Inagaki et al. (2012), Gousseau et al. (2011a,b, 2015) also conducted DNS and LES, respectively, for urban canopy flow and investigated the detailed flow structure and momentum and scalar transfer mechanism. They showed that the large-scale coherent flow structure largely contributed to momentum and scalar transfer, and the unsteady effect is one of the important characteristics of urban canyon flow. However, few studies have used the results of the DNS or LES analyses to investigate the modeling of Reynolds stress, and it is not clear how to improve the accuracy of the modeling of Reynolds stress for urban canyon flow.

In this study, we conducted the LES for flow in an idealized urban canopy which consists of aligned array of cubes. In section 2, the geometry of the target urban canyon and the condition of the numerical analysis of LES and RANS model were explained. In section 3, the reliability of the LES analysis was confirmed by comparing it to the wind tunnel experiment conducted by Uehara et al. (2000). The prediction accuracy of the RANS model was evaluated by comparing to the results of LES which were reliable enough to use as the reference data. In section 4, the validity of the modeling of Reynolds stress in the standard k-ε model (k-ε model) was investigated using the LES data. The budget of Reynolds stress transport equation was analyzed, and the mechanisms of the production, dissipation, transport, and conversion of Reynolds stress were investigated. The validity of the modeling of Reynolds stress in the k-ε model, and how to improve it, was examined using the results of the budget analysis. In section 5, we summarized the findings and mentioned some limitations of this study which is necessary to be investigated in future works. In this study, the standard k-ε model (Launder and Spalding, 1974) was used as the representative turbulence model for RANS analysis.

2. Methods

2.1. Geometry and sampling locations

Figs. 1b and 2 show the analysis domains of the LES and k-ε model, respectively. Fig. 3 shows the model of the urban canyon and data sampling locations. In this study, the analysis model was set up by referring to the experiment conducted by Uehara et al. (2000). x_i, u_i shows the components of spatial coordinate and velocity vector. i = 1, 2, 3 means the streamwise, spanwise, and vertical direction, respectively, as shown in Figs. 1 and 2. Building model blocks with dimensions H (x_1) × H (x_2) × H (x_3) (H = 100 mm) were arranged at H intervals in the streamwise direction in 10 rows, and at 0.5H intervals in the spanwise direction. The building coverage ratio of the urban block model was 33%. 5H gap between the inlet boundary and urban block model was set according to the simulation set-up recommendation of AIJ guideline. Fig. 1a shows the driver part of the LES to make the approaching flow for the urban block model. The approaching flow was made by arranging the roughness blocks in the LES. In the driver part, roughness blocks with dimensions H (x_1) × H (x_2) × 0.5H (x_3) were arranged in a staggered configuration, at H intervals for 50 rows in the streamwise direction and at H intervals in the spanwise direction. Turbulent statistics were sampled at seven locations of the central vertical section of urban canyon to consider the spatial distribution within urban canyon—the center of the urban canyon (UCC), leeward side of the urban canyon (UCL_1, UCL_2, and UCL_3), and windward side of the urban canyon (UCW_1, UCW_2, and UCW_3), as shown in Fig. 3. The profiles of turbulent statistics in the LES were averaged at the same condition locations in spanwise direction (x_2/H = 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5). Turbulent statistics were normalized by streamwise mean velocity at x_3/H = 2.0 of UCC and the height of the building model block H.

2.2. Simulation set-ups and boundary conditions

Tables 1–3 list the conditions of the numerical analysis and boundary conditions of the LES and k-ε model. In this study, the numerical analysis was performed using OpenFOAM (version 2.1.1), an open-source CFD analysis software.

In the LES, the influence of the sub-grid scale (SGS) model and grid resolution on the results was investigated. The SGS model of the LES was a standard Smagorinsky model (Smagorinsky, 1963) with a Van Driest damping function (Van Driest, 1956) in Case 32-SS, Case 16-SS, and Case 8-SS. The Smagorinsky constant C_s was set at 0.12 (Tominaga and