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Grid resolution assessment in large eddy simulation of dispersion around an isolated cubic building

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ABSTRACT

In the present paper, the influence of grid resolution on prediction accuracy of large eddy simulation (LES) of dispersion around an isolated cubic building was investigated. Several grid resolution assessment techniques in LES, namely, two-point correlations, ratio of SGS viscosity to molecular viscosity and ratio of SGS shear stress to resolved shear stress were considered. It was found that two-point correlations could be regarded as a useful method for evaluation of grid resolution. However, it was highly time consuming and required extra post-processing calculation. Also, it was shown that ratios of SGS viscosity to molecular viscosity and SGS shear stress to resolved shear stress decreased by improving grid resolution and they did not change significantly by further increasing the grid resolution. Thus, both these ratios were concluded to be an applicable technique for the evaluation of grid resolution in LES.
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1. Introduction

The prediction of plume dispersion in the lower level of atmospheric boundary layer is essential for the proper design of exhaust stacks and air intakes. However, it is difficult to predict pollutant dispersion with a certain degree of accuracy due to the existence of complex vortical structures around buildings. Li and Meroney (1983) investigated the dispersion of effluent plumes emitted on or in the near-wake region of a cubical model building experimentally. Time-averaged concentration measurements were made on the model building for three different roof vent locations and three different building orientations. It was found that the concentration level on the lee face of a model building was greatly reduced by the presence of a sharp edge on the model. In addition, the optimum location for the intake vent on the building was recommended. This experimental study has been used as a benchmark for the CFD predictions of dispersion around an isolated cubic building (Gousseau et al., 2011; Tominaga and Stathopoulos, 2009, 2010). At the present time, computational fluid dynamics (CFD) is extensively employed to study the pollutant transport around buildings (Borrego and Renner, 2007). Among the turbulence models, predictions based on the Reynolds-averaged Navier–Stokes (RANS) models did not provide precise levels of concentration, which was observed in the numerical investigation by Tominaga and Stathopoulos (2009). On the contrary, transient approaches such as the large eddy simulation (LES) which were further consistent with the instantaneous flow structure may be essential to achieve more accurate results. Hence, it is expected that the use of LES in wind engineering applications to increase significantly in the future.

In several recent works, RANS and LES approaches for isolated buildings have been compared (Gousseau et al., 2011; Iizuka and Kondo, 2004; Köse et al., 2011; Tominaga and Stathopoulos, 2010). Tominaga and Stathopoulos (2010) evaluated the accuracy of LES in modeling plume dispersion near and around a simple building model, where the mechanism for the discrepancy concerning the RANS computation was clarified. The standard Smagorinsky model with the empirical constant $C_s = 0.12$ was used for the sub-grid scale eddy viscosity model. Near the wall, the length scale was modified by a van Driest damping function and the sub-grid scale Schmidt number was set to 0.5. It was concluded that LES appears to be more accurate than RANS in predicting the time-averaged concentration field, because it captures the unsteady concentration fluctuations. Gousseau et al. (2011) performed a CFD modeling for two configurations of isolated buildings with distinctive features based on two most frequently used approaches, RANS and LES. It was shown that the proper simulation of the convective fluxes is essential to predict an accurate concentration field. More recently, Tominaga and Stathopoulos (2012) investigated the spatial distribution of the turbulent scalar flux within a building array with a point source for the simple street canyon model by both LES and RNG turbulence models. They reported that the RNG model under-estimates turbulence diffusion in the building canyon as compared with LES and there were large differences between the distributions of the estimated eddy viscosity and eddy diffusivity. It was also shown that the superiority of flow field prediction by LES has a notable influence on the concentration

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Nomenclature

⟨⟩	Time-averaged value
C	Concentration
C_s	Smagorinsky model constant
CFL	Courant–Friedrichs–Lewy number
D_m	Diffusion coefficient
D_t	Turbulent diffusivity
$\overline{f}$	Filtered scalar
I	Turbulence intensity
J_j^{SGS}	SGS scalar flux
k	Turbulence kinetic energy
S_{ij}	Rate of strain tensor
Sc_{SGS}	SGS Schmidt number
$t^* = t/T,\ T = H_b/U_H$	Dimensionless time steps
u', v' and w'	Velocity fluctuation components
u_τ	Friction velocity
y^+	Dimensionless wall distance
y_p^+	y^+ at the first point
Δ	Grid filter width
ε	Turbulent dissipation rate
λ_{uu-z}	Integral length scale based on streamwise velocity fluctuation in z direction
λ_{vv-z}	Integral length scale based on normal velocity fluctuation in z direction
λ_{ww-z}	Integral length scale based on spanwise velocity fluctuation in z direction
λ_{ww-x}	Integral length scale based on spanwise velocity fluctuation in x direction
υ_{SGS}	SGS turbulent viscosity
ρ	Density
τ_{ij}	SGS stress tensor
$\xi = x^A - x^B$	Separation distance between points A and B

Subscript

rms	root-mean-square
SGS	sub-grid scale
tur	turbulent

diffusion field. Moreover, Iizuka and Kondo (2004) studied turbulent flow over a two-dimensional steep hill with various sub-grid scale models in LES. It was found that the dynamic sub-grid scale (SGS) results were in very poor agreement with the experiment, because of its relatively inaccurate estimation of the model coefficient near the ground surface. Furthermore, effects of inlet boundary condition (Köse et al., 2011), Schmidt number (Bazdidi-Tehrani et al., 2011; Tominaga and Stathopoulos, 2007), thermal stabilities on turbulent transports (Cheng and Liu, 2011; Yoshie et al., 2011) and adjacent buildings on pollutant transport (Chavez et al., 2011) in the field of wind engineering were investigated. However, very few studies have addressed the issue of the dependence of LES results on the mesh resolution.

LES accuracy is under the direct influence of the grid resolution, because the numerical discretization error as well as the sub-grid scale model contribution (modeling error) depends on the grid resolution. Therefore, grid resolution should be evaluated carefully for well-resolved LES. Grid resolution in RANS simulations has been investigated for many years and there are even some guidelines for assessment and reporting of numerical uncertainty in such simulations (Roache, 1997, 1998; Wilson et al., 2001). Whereas, the assessment of grid resolution requirements in LES is not so straightforward. For the attached boundary layer flows, numerical simulations reported that the streamwise and spanwise resolution in viscous units should at least be approximately 100 and 30, respectively (Piomelli and Chasnov, 1996). Further, the center of the wall-adjacent cells should be located not more than one viscous unit away from the wall (Davidson, 2011). Geurts and Fröhlich (2002) proposed the activity parameter, s, which is defined as the ratio of turbulence dissipation to total dissipation, in order to evaluate grid resolution relating to LES. The modified activity parameter, proposed by Celik et al. (2005), is based on the relative Kolmogorov scale index and the relative SGS viscosity index, which are called LES_IQ_η and LES_IQ_υ, respectively. In addition, LES_IQ_k based on the resolved turbulence kinetic energy was suggested by Celik et al. (2009, 2005). Pope (2004) suggested that when 80% of the turbulence kinetic energy is resolved, the LES can be considered to be well-resolved. LES_IQ techniques have been utilized in several numerical investigations for the grid resolution assessment. Tóth and Lohász (2008) attempted to apply the LES_IQ_k for quantifying the various refinements. The method was applied to a spatially developing axisymmetric shear layer (a round jet). It was concluded that LES_IQ_k was misleading, since it could underestimate the relative importance of the grid refinement effects. Boudier et al. (2008) analyzed the convergence of LES predictions for a reacting flow in an aero gas turbine combustion chamber in terms of mesh resolution for three fully unstructured tetrahedral meshes of 1.2, 10.6 and 43.9 millions, respectively. It was found that the resolution criteria obtained from the mean velocity and reacting fields depict different convergence states. Reacting fields and more specifically combustion regimes are seen to be slightly grid dependent while maintaining mean global combustion quantities. Manickam et al. (2012) employed LES_IQ_k for quality and error assessment of LES of triangular-stabilized lean premixed turbulent flames on three grid resolutions. It was found that a coarse grid leads to an over-prediction of turbulence quantities due to low dissipation at the early stage of flow development behind the bluff body.

Freitag and Klein (2006) and Klein (2005) proposed a systematic grid and model variation (SGMV) method that evaluates the numerical error and modeling error contributions in the implicit LES based on the Richardson extrapolation. Brandt (2007) studied the applicability of Klein's (2005) approach. It was shown that the obtained order for the effect of modeling and numerical errors varied strongly as a function of the wall distance. The obtained order for the effect of modeling error can be both positive and negative values whilst the numerical error had only negative values. Therefore, it was concluded that neither numerical nor modeling errors could be evaluated using the Richardson extrapolation. Gousseau et al. (2013) performed large eddy simulation of wind flow around a high-rise building. Several cases were analyzed using two different grids and with two different SGS models, namely, the standard Smagorinsky model and its dynamic version. It was shown that generation of inflow turbulence based on the vortex method provided accurate results. Moreover, the agreement between numerical and experimental results was quantified by different validation metrics and the SGMV technique was employed to provide estimates of the modeling and numerical error contributions.

Davidson (2009) investigated the applicability of several grid resolution assessment methods to fully developed turbulent channel flow at a Reynolds number of 4000, based on the friction velocity and half the channel height. These methods included energy spectra, dissipation energy spectra, two-point correlations,

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