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Large-eddy simulation of concentration fluctuations in an actual urban area

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SUMMARY:
In this study, we investigated the performance of large-eddy simulation (LES) to predict pollutant gas dispersion emitted from a point source near the ground in a high-density urban area. We conducted a wind tunnel experiment of gas dispersion using a fast flame ionization detector (FID) for numerical validation. The LES results were in good agreement with the experimental results in mean concentration. In addition, the statistical higher-order moments of concentration fluctuation, which define the shape of the concentration probability density distribution, were examined. LES well reproduced the statistical characteristics of the concentration fluctuation at several points, including a high-concentration area formed at the lower level on the overpass and wake region of a tall building where the concentration was vertically constant under the influence of the flow field. Moreover, the gamma probability density function (PDF) effectively represented the shape of the concentration PDF in the actual urban area obtained by the LES.

Keywords: Pollutant dispersion, Large-eddy simulation, Concentration fluctuation

1. INTRODUCTION

Pollutant dispersion can negatively impact urban environments and pose health risks to pedestrians. For assessing risks related to the release of hazardous materials (e.g., toxic gases and flammable gases), it is necessary to predict not only the mean concentration but also the instantaneous peak concentrations and the statistical characteristics of the concentration fluctuations, such as probability distribution functions (PDFs). As reviewed by several papers (e.g., Cassiani et al., 2020), full-scale field measurements and laboratory experiments have been conducted to study concentration fluctuations of a passive scalar released from continuously emitting sources. However, studies in actual urban areas in which flow and concentration fields are highly complex due to the influence of building configuration are limited. Furthermore, only a few studies have investigated the relationship between the statistical properties of concentration fluctuations and turbulent structure of urban flow fields. In this regard, large-eddy simulation (LES) has an advantage over measurements with respect to its potential in providing spatial distributions of wind velocity and concentration concurrently. This study aims to investigate the performance of LES to in predicting concentration fluctuations in a highly dense city as a first step toward elucidating the relationship between concentration fluctuations and turbulent structure. We compared the results of LES and a wind tunnel experiment in the mean concentration and statistical moments, which define the shape of the concentration PDF.

2. EXPERIMENTAL SETUP

The experiment of gas dispersion was conducted in a wind tunnel under isothermal conditions, with a working section of 19.9 m length, 3.5 m width, and 2.5 m height. The wind tunnel model was built at a scale of 1:600 to represent an actual urban area with densely arrayed tall buildings, as shown in Fig. 1 (details of the wind tunnel model are described in Nozu and Tamura, 2012). The power law exponent of the vertical profile of the approach flow was 0.2. The streamwise velocity measured at the reference height H = 0.124 m was set as U_H = 2.0 m/s. In our experiment, 100% ethane (C_2H_6) was released as a tracer at a steady rate from a point source at a diameter of 5 mm on the overpass. The exhaust velocity of the tracer gas W_e was set as 0.5 m/s (W_e/U_H=0.25). Concentrations were measured using a fast flame ionization detector (FID) at the measuring points shown in Fig. 1(b). At each measuring point, sampling data were obtained in 180 s at 1 kHz. All measured concentration values C are presented as non-dimensional concentration C^*, normalized by the reference velocity U_H, reference height H, and flow rate Q_0 ($C^* = CU_HH^2/ Q_0$).

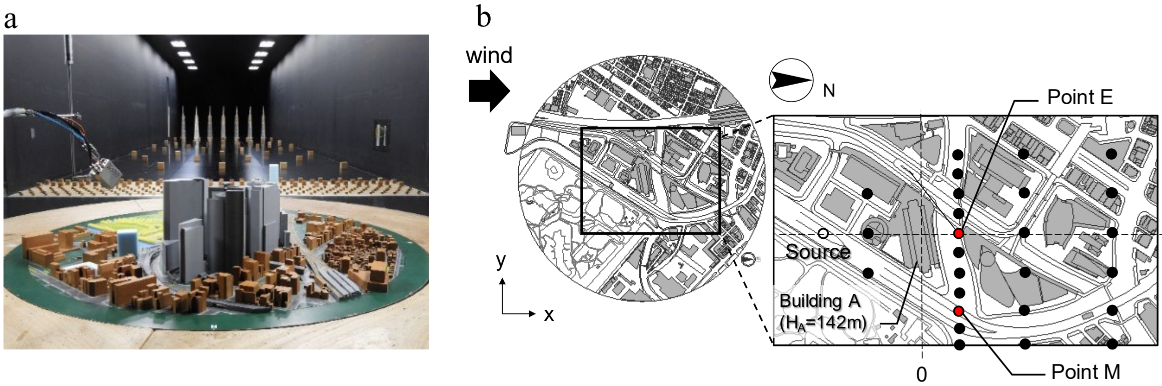

Figure 1. Target area of the experiment and large-eddy simulation. (a) Photograph of the wind tunnel model and (b) target area, wind direction, and measurement locations of profiles.

3. COMPUTATIONAL SETUP

We conducted the LES following the conditions in the experiment. In the present study, OpenFOAMv2006 was employed to solve the continuity, Navier–Stokes, and scalar transport equations. The pressure implicit with splitting of operators (PISO) algorithm was applied for the coupling of the continuity and Navier–Stokes equations. The wall-adapting local eddy-viscosity (WALE) model was adopted for the subgrid-scale model. The Schmidt number for the molecular diffusion of the tracer gas was set to 1.0. The subgrid-scale Schmidt number was set to 0.5. A blending scheme of 95% second-order central difference and 5% first-order upwind difference was applied to the convection term in the Navier–Stokes equation. The total variation diminishing (TVD) scheme was applied to the convection term in the scalar transport equation. The calculation was conducted for 100 s, and statistical values were obtained from the last 60 s.

4. RESUTS AND DISCUSSION

4.1. Concentration field

Fig. 2(a) illustrates the isosurfaces of the mean concentration C^* = 0.1, 0.4, and 1.2 predicted by the LES. The mean concentration was significantly large at a lower height along the overpass downwind from the source point. A relatively high-concentration region was formed in the wake of building A. The mean concentration in the LES compared with the experimental value is shown in Fig. 2(b). The mean concentration field obtained by the LES corresponds well with the experimental results.

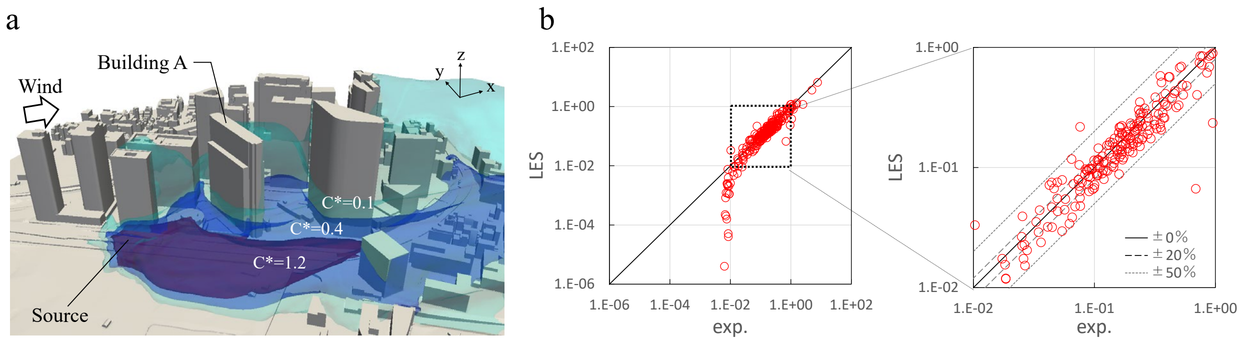

Figure 2. Results of the mean concentration C^*. (a) Isosurfaces of the mean concentration predicted by the LES and (b) scatter plot of the mean concentration obtained from the wind tunnel experiment and LES.

4.2. Statistical characteristics of concentration fluctuation

We compared the statistical characteristics of the concentration fluctuation of the experimental data and LES results. Fig. 3 illustrates the vertical distributions of the mean concentration, concentration fluctuation intensity i_c, skewness, and kurtosis in the wake of building A (point E) and above the overpass (point M). The LES reproduces the tendency of the distribution of statistical values effectively, although a discrepancy in the concentration fluctuation intensity i_c is observed above 100 m at point M, attributed to the small mean concentration.

The mean concentration above the overpass (point M) remains at a high level near the ground and decreases rapidly upward. Conversely, i_c at point M increases while moving toward a higher altitude, and similar behavior is also observed for skewness and kurtosis. In the wake region (point E), the mean concentration is relatively constant in the z-direction. The vertical variations in i_c and higher-order moments at point E are smaller than those at point M.

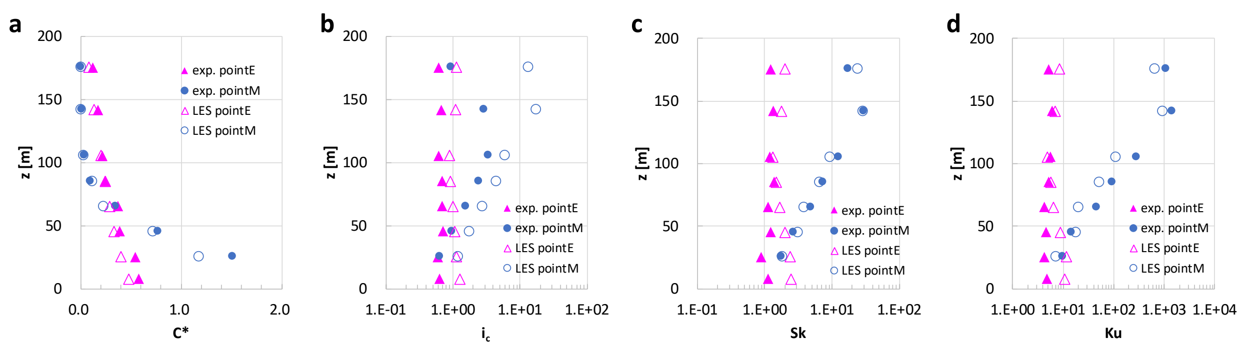

Figure 3. Vertical profiles of the statistical moments of the concentration fluctuation at points E and M. (a) Mean concentration C^*, (b) concentration fluctuation intensity i_c, (c) skewness Sk, and (d) kurtosis Ku. Results are reported in full scale.

For practical purposes, several PDF models have been tested to reproduce the concentration PDF of a passive scalar released from a point source. More recent results have shown the choice of the gamma distribution as the best PDF model for the concentration from a point source over a certain range of downwind distances from the source (e.g., Efthimiou et al., 2016, Ardeshiri et al., 2020). The intensity of the concentration fluctuation is used as a parameter to characterize the shape of the gamma PDF (Yee et al., 1993, Nironi et al., 2015). The values of skewness and kurtosis at each measuring point obtained by the LES as a function of i_c^2 are shown in Fig. 4. For comparison, the theoretical relationships between skewness (kurtosis) and i_c^2 generated by the gamma distribution are depicted in Fig. 4. The gamma distribution provides a good overall fit for the LES data, with a wide range of i_c. The gamma distribution appears to provide a good match to the concentration fluctuation data over the range of turbulent flow conditions.

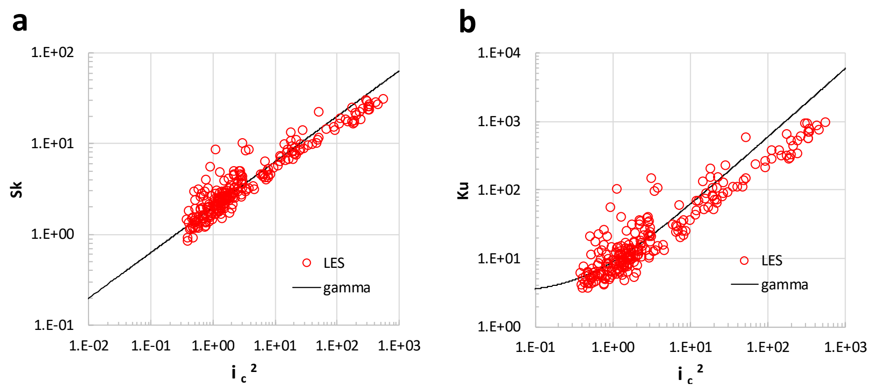

Figure 4. Higher-order moments of the concentration fluctuation as a function of i_c^2 at each measuring point obtained by the large-eddy simulation. (a) Skewness *Sk* and (b) kurtosis *Ku*.

5. CONCLUSIONS

To evaluate the LES prediction of pollutant concentration fluctuations in an actual urban area, we compared the results of the wind tunnel experiment and LES on an exhaust gas emitted from a point source near the ground in an actual city. For the mean concentration, the LES results were in good agreement with the experimental results. The vertical profiles of the concentration fluctuation statistics predicted by LES showed a similar tendency to that of the experiment above the overpass, where a high-concentration region was formed at the lower level, and the wake region of the tall building, where the concentration was vertically constant under the influence of the flow field. Gamma PDF fitted well with the concentration fluctuation data obtained by the LES over the range of turbulent flow conditions.

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