LES PREDICTION OF TURBULENT WIND AND GAS DISPERSION IN A CITY

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Abstract: We have conducted LES (large eddy simulation) for turbulent wind flows and dispersion of hazardous gas emitted from a point source on the ground in a large city, Tokyo. Also, for numerical validation, wind tunnel tests using a Dynamic Particle Image Velocimetry (DPIV) and tracer gas measurement system are introduced to estimate turbulence statistics of wind and gas concentration inside the compacted tall buildings. We elucidate the predictive accuracy of LES based on the wind tunnel test data. Finally, we discuss the meaning and the potential of LES prediction for dispersion problems in a complex urban area, comparing with the RANS results.

Key words: LES, wind tunnel test, DPIV, gas dispersion, turbulent wind, urban area

INTRODUCTION

In the event of an accidental gas leakage from a chemical facility or a delivery vehicle in an urban area, leaked gases could have a serious impact on the human body even after a very short exposure time. Therefore, it is important to estimate not only the long-time averaged value but also the instantaneous value of a hazardous gas concentration. Time variation of gas concentration is determined dominantly by the unsteady flow field, which contains eddies of various scales. For numerical investigation of concentration fluctuation, we need to conduct time-dependent simulation such as large eddy simulation (LES) that accurately represents unsteady phenomena of turbulent flows. Turbulence of urban wind consists of eddies inherent in the approaching flows and those locally generated by various complicated configurations of the urban surface. Therefore, time sequential data of inflow turbulence for the computational domain should be appropriately generated by auxiliary simulation of boundary layer flows. Also, a numerical model that individually reproduces actual buildings or structures with various shapes on the ground should be constructed using geographic information system (GIS) data. Thus far the present authors have applied the LES technique to prediction of turbulent wind around a building complex embedded inside an actual urban boundary layer (Nozu and Tamura, 2008; Nozu et al., 2009) and confirmed sufficient accuracy of the present LES model by comparing its simulated results with field measurement data.

In this study, we conduct LES for not only turbulent wind flows but also dispersion of hazardous gas emitted from a point source on the road in the center of a large city, such as Tokyo. Also, for numerical validation, wind tunnel tests using a Dynamic Particle Image Velocimetry (DPIV) and tracer gas measurement system are introduced to estimate turbulent quantities of wind flow and gas concentration among dense buildings in a city. We elucidate the predictive accuracy of LES based on the wind tunnel test measurements. Finally, we discuss the future potential of the present LES prediction for dispersion problems in a complex urban area, comparing with the RANS (Reynolds averaged Navier-Stokes) results.

WIND TUNNEL TEST AND LES MODEL

For validation of LES, we conducted experiments for turbulent wind flow and gas dispersion in a wind tunnel with a working section 3.5m wide, 2.5m high and 19.9m long. Figure 1 shows a photograph of the experimental set-up representing densely arrayed tall buildings within an urban boundary layer. The approaching flow simulates the developing turbulent boundary layer by using the blocks placed on the upwind region of wind tunnel. For urban area, the average height of the buildings was about 180m and the height of the tallest was 216m.

DPIV system was used to measure the time variations of the flow fields. Sampling frequency was set to 500Hz. For the concentration measurement, Ethane (C2H6) was used as the tracer gas. The tracer gas was released from a 5mm-diameter hole in an elevated highway on the side of the packed tall buildings, and its concentration was measured by a hydro-carbon meter. The experimental reference wind speed (UH) at a scale height (H) of 74.5m was set at 2m/s, and the exhaust velocity of gas (V) was 0.5m/s (exhaust momentum ratio V/UH=0.25). Concentration data were expressed in terms of a non-dimensional concentration coefficient C* (=CUH2/Q, C: measured tracer gas concentration in ppm, H: a typical unit of length, Q: emission rate).

For LES model the governing equations are the filtered forms for continuity, the incompressible Navier-Stokes and the scalar conservation equations. Concerning the sub-grid scale modeling, the Smagorinsky-type eddy viscosity model with dynamic procedure was employed for both the flow and scalar fields. The coupling algorithm of the velocity and pressure fields was based on the MAC method with the Adams-Bashforth scheme for time integration. For the spatial discretization in the governing equation of the flow field, a fourth-order central difference scheme was used. For the concentration field, the CIP scheme was employed for the convection term to avoid the occurrence of unphysical overshooting for concentration.
Figure 2 illustrates a schematic of the computational model for LES. To generate the turbulent boundary layer, we set up a driver region consisting of two domains (Domain 1 and Domain 2). Domain 1 generated the neutral turbulent boundary layer over a rough surface by using a re-scaling technique (Lund et al. 1998; Nozawa & Tamura, 2002), and Domain 2 developed a boundary layer and reached it to the equilibrium state. Domain 3 reproduced the main region in the Tokyo central area 1.75km by 1.0km and the boundary shape at the bottom surface was set by the GIS data, which represented a realistic urban aspect with low-, middle- and high-rise buildings in Tokyo. Table 1 shows the numerical conditions on the domain size, grid points and grid size of the computational domain.

![Figure 2](image.png)

**Table 1: Computational domain, grid points and grid size**

<table>
<thead>
<tr>
<th>Computational domains</th>
<th>Streamwise(y)</th>
<th>Spanwise(x)</th>
<th>Vertical(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain 1</td>
<td>5.0δ + 4.1δ</td>
<td>3.5δ</td>
<td>1.6δ</td>
</tr>
<tr>
<td>Domain 2</td>
<td>156 + 151</td>
<td>700</td>
<td>400</td>
</tr>
<tr>
<td>Domain 3</td>
<td>18.9 + 2.95</td>
<td>2.95</td>
<td>2.95 - 2.66</td>
</tr>
</tbody>
</table>

Figure 3 shows vertical profiles of wind velocity at the driver region obtained by LES and generated in the wind tunnel. Both profiles of mean and rms values show almost good agreement, so it can be determined that the inflow conditions have been appropriately given for comparison of LES and experiment.

**WIND VELOCITY FIELD**

Figure 4 shows a horizontal section of the time-averaged wind velocity field at a height of 25m obtained by LES. It can be seen that the high-speed wind velocity region is formed at the left side of Building-A and both sides of Building-B. In particular, the left side area of Building-B followed by the main street between the compacted buildings forms the so-called street canyon, where the wind speed increases considerably by the sheltering effect. We can also see that the separated shear layer from Building-A extends toward the front face of Building-B and is divided into two directions, one of which forms a wake region behind Building-A.

![Figure 4](image.png)

Figure 5 compares the DPIV and LES results of averaged horizontal wind velocity distribution in the sampling area (see Figure 5(a)). According to the DPIV results, a small wake behind Building-A at 25m height enlarges at higher position of 105m. As a result, the high speed velocity region at the right front side of Building-B shrinks as height increases. These tendencies can be seen in the LES results, but this high wind velocity by LES is higher than the DPIV results.

![Figure 5](image.png)

Figure 6 compares the DPIV and LES results of fluctuating wind velocity (rms values) distribution in the same sampling area. According to the DPIV results, the fluctuating velocity is large around the shear layer separated from the side of Building-A. This is attributed to a periodic unsteadiness in the position of the shear layer. However, the distribution shape at 25m height is different from those at 65m and 105m height, and the position of the large fluctuating velocity at 25m height is a short distance from the side of Building-A. This is attributed to the fact that a strong downwash wind comes down from an upper level. These tendencies can be seen in the LES results.
Figure 7(a) and (b) show time averaged 3D streamlines for tall buildings. The starting point of a fluid particle in Figure 7(a) is set on the ground surface near the emission point of gas dispersion. Here we can also confirm that the wind flow turns around the left front corner of Building-A and divides into two directions at the front face of Building-B. One travels leeward near ground level, and the other enters between Building-A and Building-B, then rises up in the wake region behind Building-A. Also, Figure 7(b) represents time averaged 3D streamlines released from three different levels upstream. At low height, the streamlines (red color) largely separate from the side of Building-A and travel leeward. At middle height, the streamlines (green color) enter between Building-A and Building-B. In particular, downwash has occurred at the side of Building-A under the stagnation point height, and this causes the wake of Building-A to be small at 25m height. At high height, the streamlines (blue color) form a large wake.

Figure 7. Time averaged 3D streamlines for tall buildings by LES

(a) Released from near the emission point  (b) Released from three different levels
GAS DISPERSION FIELD

Figure 8 shows the time averaged concentration field of a gas plume emitted from the point source on the elevated highway. Near ground level (z=25m), the gas emitted from the source mainly passes a short distance from the closely spaced tall buildings and a high concentration area is formed a short distance from the left side of Building-A. Also, we can see that a high concentration is maintained within the street canyon. At the front face of Building-B, a portion of gas is introduced into the wake of Building-A. As a result of penetration and mixing, a relatively high concentration region appears as far as higher position in the wake of the tall buildings.

Figure 9 shows vertical profiles of time averaged concentrations at various locations along the downstream direction. Near the emission point, the gas does not disperse to a higher position, but indicates a large concentration at lower position. However, the averaged concentrations inside closely spaced tall buildings have an almost equal value, regardless of the distance from the emission point to the measurement point. That is to say, it can be confirmed that the near-ground concentration near the emission point is higher than the above far-ground concentration. Horizontally far from the emission point, the concentration becomes vertically constant. LES reproduces these tendencies.

Figure 10 represents iso-surface and contour (at 65m height) of the averaged concentration and the peak concentration. For the closely spaced tall buildings, it is found that the average concentration becomes higher in the building wake where wind velocity is low. In contrast, the peak concentration becomes higher at the front-side area of a high-rise building where wind velocity is high, and becomes lower in the building wake. Because gas entrainment at the edges of closely spaced tall buildings is very intermittent, the peak concentration increases in the high wind area. RANS cannot reproduce the periodic concentration fluctuation due to the vortex shedding as well as these intermittent fluctuations of concentration (Shirasawa et al. 2008). However, it is found that LES can reproduce these phenomena.

LES VERSUS RANS

We also carried out RANS simulation by use of the commercial code, FLUENT. The standard k-ε model is employed for turbulence model. As a result of unstructured grid system, building shapes are represented by smooth lines. The convection term is discretized by QUICK scheme for sufficient numerical stability.

Figure 11 shows the comparison between LES and RANS results of time averaged wind velocity field and concentration field at a height of 105m. The wake of the wind flow around the pack of tall buildings becomes wider and larger for RANS, compared to LES. It is due to the effects of too much eddy viscosity of RANS adopted as turbulence modelling in the wake. The concentration field of LES becomes smaller in the wake than the RANS results. Unsteady phenomena by the motion of the shear layer and the vortex shedding cause enhance of the gas dispersion among the tall buildings. While, RANS has such no convective act that the gas, entering inside the wake once, accumulates and stagnates among the buildings.
Figure 12 represents the vertical profiles of time averaged concentration in the wake (No.05) and on the left side (No.16) of Building-A. In the wake region, it can be confirmed that the gas diffuses upward and reaches the height of Building-A. The concentration is vertically constant. Conversely, the gas concentration of No.16 remains at a high level in the lower region and decreases rapidly upward. Quantitative agreement with experimental data is better for the LES results than the RANS results. LES results successfully simulate the balanced circulation of dispersion where the gas entrains in the wake and also goes out from the wake, accompanying with the unsteady flows.

CONCLUDING REMARKS
We carried out wind tunnel tests as well as LES for turbulent wind flows and dispersion of gas emitted from a point source on the ground in actual urban areas. The following results were obtained.

1. Concerning the predictive accuracy for the flow-field, we can confirm that LES can reproduce the DPIV flow patterns in the wake region and the high velocity region around a high-rise building.
2. Concerning the gas dispersion prediction, the LES results were in good agreement with the wind tunnel test result, in which a high concentration area appears at the lower level on the side of a high-rise building and the concentration is vertically constant in the wake region under the influence of the flow-field.
3. Average concentration becomes higher in the low-wind areas such as a building wake. In contrast, since the gas entrainment at the edges of closely spaced tall buildings is very intermittent, the peak concentration becomes higher in this unsteady high-wind area.
4. RANS cannot reproduce contribution of the periodic concentration fluctuation due to the advection effect, such as unsteady separated shear flows and vortex shedding. So, RANS indicates high concentration in building wake region.

REFERENCES