Cross Comparisons of CFD Results of Wind and Dispersion Fields for MUST Experiment: Evaluation Exercises by AIJ

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Abstract
In order to apply Computational Fluid Dynamics (CFD) techniques to estimate pollutant dispersion in urban areas, it is important to assess the performance of numerical models used to estimate these phenomena. Recently, the MUST (Mock Urban Setting Test) has often been adopted as a test case for evaluating numerical models for micro-scale urban meteorology. This paper presents the results of model evaluation exercises carried out using MUST based on the Architectural Institute of Japan (AIJ) experience. The results of model evaluation exercises conducted by AIJ are broadly consistent with the results obtained by the COST group. However, the variety of results by each computation can be minimized by setting standard computational conditions. All computations including both RANS and LES show good agreement with wind experiment data. In general, LES cases show comparable accuracy to RANS in predicting U and W. However, LES shows better agreement than RANS in predicting TKE and concentration.

Keywords: CFD; dispersion; the MUST case; cross comparison; AIJ

1. Introduction
AIJ (Architectural Institute of Japan) has provided guidelines for practical applications of CFD (Computational Fluid Dynamics) to the pedestrian wind environment around buildings (Tominaga et al., 2008). In preparing these guidelines, many comparative and parametric studies on various building configurations were conducted by the AIJ Working Group (Tominaga et al., 2004; Yoshie et al., 2007). These investigations mainly targeted problems of strong wind around high-rise buildings. However, air pollution in weak wind regions such as behind buildings and within street canyons is now broadly recognized as a serious environmental problem. Presently, CFD is widely used as an analytical tool for evaluating the polluted urban environment (e.g. Bady et al., 2009). In order to apply CFD techniques to estimate pollutant dispersion in urban areas, it is important to assess the performance of numerical models used to estimate these phenomena. Action on extending the guidelines to urban pollutant problems has been continuing (Yoshie et al., 2011).

Recently, European researchers in the field of micro-scale meteorology have bundled their activities in the COST action 732 (2005-2009), Quality assurance and improvement of micro-scale meteorological models, to propose and test a new protocol for the evaluation and quality assurance of numerical models (Britter and Schatzmann, 2007). In this work, MUST (Mock Urban Setting Test) was selected to test the protocol's validity. Wind tunnel measurements on a scale model (1:75) were carried out at the University of Hamburg. Several European groups of numerical modelers simulated the wind tunnel MUST experiments following the model evaluation protocol and methodology. The results of the exercise were compiled (e.g. Olesen et al., 2008; Schatzmann et al., 2009; Di Sabatino et al., 2011). They concluded that flow and concentration model...
results compare relatively well with the measurements and the prediction for the streamwise velocity component is better than for the vertical velocity component. They also pointed out that the models show some weaknesses in predicting complex flow, especially the turbulent structure of flow in specific cases. However, at the same time various parameters were changed concerning their comparisons, except in the case of studies carried out by individual institutions. Therefore, although the applicability and suitability of the protocol is confirmed, it is difficult to assess differences among different simulation results attributed to many different parameters. Furthermore, they mainly used statistical analyses based on various metrics proposed in the literature. It was pointed out that this type of analysis is helpful in estimating errors in models, but can lead to misleading conclusions due to the limited number of experimental data (Santiago et al., 2010).

In order to precisely assess the performance of these numerical models, it is necessary to investigate the reproduction of flow and dispersion structure in detail after the computational conditions are consolidated. This paper presents the results of model evaluation exercises carried out using MUST based on AIJ experience.

2. Computational Conditions

2.1 Boundary conditions

For MUST, two wind directions were examined during the COST action. However, only results for the array skewed at $-45^\circ$ to the approach flow are presented here, because concentration measurements were not available for the other case.

The basic computational conditions are set by an organizer so that they conform to the AIJ guidelines as shown in Table 1. In this process, the organizer referred...
to the adequate conditions, i.e., grid arrangements, boundary conditions, etc., which provided modest results in the exercises by the COST group (Schatzmann et al., 2009), while they had a very wide variety in the computational conditions. The computational domain is determined as shown in Fig.1. and is not treated as a parameter. The source exit is explicitly modeled as a velocity inlet with a uniform velocity profile.

2.2 Computed cases

The contributing cases are summarized in Table 2. Seven groups submitted a total of eight datasets of results obtained by different CFD codes. In this paper, computations based on the standard k-ε model (SKE) are picked up in RANS (Reynolds-Averaged Navier-Stokes) computations. Though other types of k-ε model, e.g. the RNG model and the Realizable model, have been compared in the exercises, there are small differences among them. For grid discretization, there is one difficulty in this case study. Because the measurements of the containers are slightly irregular, unstructured grids must be used to represent their configuration exactly in the computations. However, since the Cartesian grid system is adopted in cases NGU, OB1 and OB2, the containers are modeled with a staircase pattern. Grid sensitivity is checked in each case. The numbers of grids ranged from 1.1 to 7.0 million. The basic performance of these computational models and the theories applied to fundamental configurations were discussed and evaluated in previous research by the authors (Tominaga et al., 2004; Yoshie et al., 2007).

3. Results and Discussion

3.1 Comparison of metrics

Several metrics for evaluation are introduced in the COST exercise (Britter and Schatzmann, 2007). Some of those obtained by the present computations are compared in Table 3. Values relating to velocity (U, W, TKE) and non-dimensional concentration (C*) are calculated for the xz plane (498 points) and the xy
plane (256 points). The prediction accuracy for the streamwise velocity component $U$ is better than that for the vertical component $W$. Relatively poor results for the NGU case are caused by the fact that the container shape is represented by the "staircase" form. Generally, the results obtained by RANS models here are well...
consistent with the results from the COST exercises (Olesen et al., 2009; Schatzmann et al., 2009). In the LES cases (OB1 and OB2), the metrics are generally better in TKE and $C^*$, although the metrics of $U$ and $W$ are comparable with the RANS cases (Santiago et al., 2010). However, it is hard to assess the differences among flow reproduction and dispersion structure of the various cases through differences in the metrics.

### 3.2 Comparison of velocity fields

In order to investigate the reproduction of flow structure near the source point in detail, prediction results in velocity fields are compared at six vertical lines indicated in Fig.2. Fig.3. shows the comparison at lines No. 1 and 3, which are representative of 'narrow streets' (COST732, 2009). At line No. 1, the streamwise velocity $U$ obtained by all RANS cases, which show little difference, are close to that of the experiment. The LES cases (OB1 and OB2) underestimate the $U$ values near the ground. Most of the computations also reproduce well the $W$ and TKE values in the experiment. On the other hand, at line No. 3, all computations except for the NGU case underestimate the $U$ values under the container height. The values of TKE in all RANS cases except for OB1 are smaller than those of the experiment. This underestimation of TKE is consistent with the steep velocity gradient observed in $U$ due to small momentum mixing. It should be noted that the actual TKE values can be larger because the experimental TKE values are calculated by two components. Generally, the variety of results by each RANS computation can be minimized by setting standard computational conditions. Different tendencies in the distributions of the NGU, OB1 and OB2 cases including other lines can be explained by the separation point around the containers being slightly different due to the modified representation of the container shape.

Fig.4. shows the comparison at lines No. 2 and 4, which are representative of 'wide streets'. The velocity vectors obtained by the NIT case at the vertical section crossing the source exit and aligning with lines No. 2 and 4 are indicated in Fig.5. A downwash flow is observed between the containers around the source exit. All computations except for NGU show good agreement with the experiment in $U$ values for both lines. The differences among the computational cases are small. However, the values of the $W$ component are much smaller than those by the experiment for both lines. This means that the downwash flow between the containers is not correctly reproduced in the computations. In general, the two LES cases, especially OB1, show better agreement with the experiment in the $W$ and TKE distributions than the RANS cases. This is mainly because the RANS model cannot reproduce the intermittent momentum exchange between the canopy between the containers and the upper flow, which is dominant in the flow structure for 'wide streets' (Salim et al., 2011; Tominaga and Stathopoulos, 2011). Therefore, momentum diffusions in the RANS computations are underestimated there. The NGU case overestimates the TKE value around the containers because the containers are represented in "staircase" form. Therefore, the downwash flow, which can be observed in other computations and the experiment, is not reproduced due to the overestimation of TKE.

Fig.6. shows the comparisons for lines No. 5 and 6, which are representative of 'crossings'. On line No. 5, all computations show better agreement with the experiment in $U$ than the other lines, although they are slightly underestimated near the ground. The differences among the computations are smaller than those for the other lines. The values of TKE and $W$ are underestimated as well as the lines for 'wide streets'. It is clearly shown for line No. 6 that OB1 succeeds in reproducing the distributions of TKE and $W$.

As described above, the flow structure between containers is very complicated and it is hard to identify the differences among reproductions in the models by comparing the specified line distributions. Fig.7. compares the difference between the contours of $W$ for TPU and OB2 as a typical example. For TPU (SKE), a large upward flow is observed in front of the windward side containers. On the other hand, for OB2 (LES), no such upward flow is observed there, but is observed behind the containers. This flow structure is greatly affected by the property of the incoming flow. That is, the flow structures reproduced by each case are very different in the canopy of the container. It should be noted that such differences between the observed flow structures of RANS and LES hardly affect the similarity in the hit rate between the two computational approaches (Santiago et al., 2010).

### 3.3 Comparison of concentration fields

Fig.8. shows the horizontal distributions of non-dimensional concentration $C^*$ at different cross sections perpendicular to the wind directions shown in Fig.2. All RANS computations have sharp peaks around $Y=-20m$. However, the two LES cases do not show such peaks. The maximum values obtained by LES agree well with that of the experiment. It can be said from these results that the RANS models underestimate the horizontal distribution of concentration at an earlier stage of concentration diffusion. This point is clearly shown in Fig.9., which
indicates the contours of horizontal distribution of C* at the same height as the values appearing in Fig.8. The same tendency is reported in the previous study for the MUST case comparing LES and RANS (Dejoan et al., 2010). Such differences between near-field concentration diffusions of RANS and LES have also been examined in previous studies (Tominaga and Stathopoulos, 2010; Gousseau et al., 2011; Salim et al., 2011; Tominaga and Stathopoulos, 2011). This difference can also be affected by the difference in reproduction of the flow structure near the containers, as shown in Fig.7. The concentration from the source is transported largely due to the strong upward wind behind the upwind containers. The prediction accuracy of the flow separation at the sharp edges of the obstacles appears to be crucial for a proper simulation of concentration.

4. Conclusions
The results of model evaluation exercises conducted by AIJ are broadly consistent with the results obtained by the COST group. However, the variety of results by each computation can be minimized by setting standard computational conditions. All computations including both RANS and LES show good agreement with wind experiment data. In general, LES cases show comparable accuracy to RANS in predicting U and W. However, LES cases show better agreement than RANS in TKE and concentration. This is because LES can reproduce the concentration diffusion in the canopy between the containers near the source, because LES can capture intermittent and unsteady fluctuations of the flow and dispersion fields. It is difficult to assess this type of difference in flow and diffusion structure through metrics and a limited number of measured points. It should also be considered that the
prediction accuracy of the flow separation at the sharp edges of the obstacles appears to be crucial for proper simulation of concentration.

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References

Fig. 8. Horizontal Distributions of Non-dimensional Concentration $C^*$ at Cross Sections Perpendicular to Wind Direction

Fig. 9. Horizontal Distributions of Non-dimensional Concentration at $z=1.275m$


