LES AND RANS SIMULATIONS OF THE MUST EXPERIMENT. STUDY OF INCIDENT WIND DIRECTION EFFECTS ON THE FLOW AND PLUME DISPERSION

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Abstract

In this study, we propose to assess and compare the performance of LES and RANS methodologies for the simulation of pollutant dispersion in an urban environment by making use of field and wind tunnel measurements of the MUST experiment configuration. First, the proposed analysis addresses the relevance of taking into account the small geometrical irregularities of the obstacle array in the computations. For this, local and spatial-averaged time mean flow properties are compared for two geometries, one with a perfect alignment of the containers and another one including the irregularities present in the experiment. In both geometries the incident flow is orthogonal to the front array of obstacles. The second part of this study presents simulations with different approaching wind directions to analyse the effect of small changes in the incident wind direction on the flow and on the plume dispersion. In this second part, the mean concentration field is compared with the experimental data and an analysis that relates the channelling effects with the plume deflection is provided.

Key words: MUST experiment, LES, RANS, Urban Canopy Layer, Urban Dispersion

1. INTRODUCTION

Nowadays, air pollution is considered a great environmental problem in many cities and the improvement of the urban air quality one of the most important environmental challenge. Inside the city, where an important part of the emissions are released, the interaction between atmospheric flow and urban geometry produces complex flow patterns. Hence, it is difficult to determine pollutant concentration inside the urban canopy. In this context computational fluid dynamics (CFD) models may be useful. These models can simulate the flow and dispersion in urban areas with high resolution (~ m) by including explicitly the buildings in the computations. In this study two different CFD approaches are used: large eddy simulations (LES) and Reynolds-averaged Navier-Stokes (RANS). LES methodology, by means of a filtering operation applied to the Navier-Stokes equations, resolves explicitly the dynamics of the unsteady large scales of turbulence while parameterising the small scale motions. On the other hand, RANS approach integrates the whole turbulence spectrum so that turbulence modelling assumptions are required for the statistical closures. The LES computational cost is approximately two orders of magnitude greater than the RANS one.

The urban configuration chosen for this study is the Mock Urban Setting Test (MUST) case. The MUST experiment was set up in the great basin desert (USA) to investigate the dispersion of a passive scalar within a model of an urban environment represented by an almost regular array of rectangular containers (Biltoft, 2001). The array of the MUST field experiment is composed by 12 by 10 containers placed in an aligned configuration. Each container is 12.2 m long, 2.42 m wide and 2.54 m high, except the VIP container (H5) that was 6.1 m long, 2.44 m wide and 3.51 m height (Figure 1). The containers are not perfectly aligned. In average, the obstacle spacing is $<L_x>/h = 5.08$ in the lengthwise direction (x-direction) and $<L_y>/h = 3.11$ in the spanwise direction (y-direction), where h defines the height of the standard container. Beside the filed experiment, a scaled wind tunnel experiment of the MUST configuration was also performed by Bezpalcova (2007).

The objective pursued in this work is twofold: compare LES and RANS simulations to evaluate the effect of geometry irregularities by considering local but as well spatially average mean flow quantities in a configuration with an incident wind perpendicular to the front array, and assess the effect of small changes of the incident wind direction on pollutant dispersion.

2. MODEL DESCRIPTION

The RANS calculations were carried on by making use of FLUENT (FLUENT, 2005) code to solve the steady incompressible Reynolds-averaged Navier-Stokes equations. The turbulence closure used is the standard k-ε model. The evolution of the mean concentration is given by a transport equation for a passive scalar pollutant.

The LES simulations were performed using as baseline code the open source CFD code based on the Field Operation and Manipulation C^{++} class library for continuum mechanics (OpenFOAM, 2006). The large-scale flow motions are described by the filtered incompressible Navier-Stokes equations and the contribution of the subgrid-scale is modelled by the standard Smagorinsky model. The concentration evolution is given by a filtered passive scalar equation.

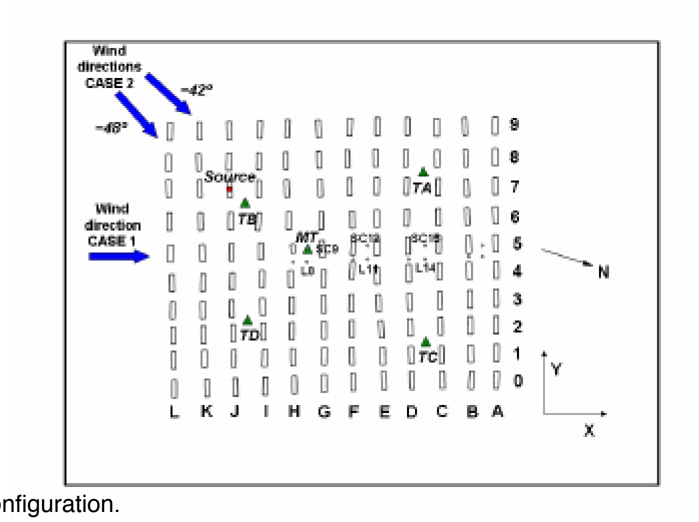

Figure 1. MUST configuration.

3. CASE 1: INCIDENT FLOW PERPENDICULAR TO THE ARRAY

In this case LES and RANS simulations are performed for the MUST configuration with the incident flow directed perpendicularly to the front array of containers (Figure 1). Two MUST configurations are taken into account: an irregular one and a regular one. The irregular configuration is exactly the same geometry as the experimental one including the alignment errors of the array. The regular configuration considers all of the containers with the same size and shape and perfectly aligned. Using these configurations, the influence of the small geometry irregularities on the flow is studied. The grid resolution of the LES presented (ten cells or more to describe the urban canopy) fulfils the condition suggested by Tseng et al. (2006) (minimum resolution of 6-8 grid points across the buildings to apply LES in atmospheric boundary layer flow over urban canopy). A similar grid resolution was used for RANS simulations.

3.1. Comparison against experimental data

LES and RANS simulations for the irregular case are compared against the experimental data from the wind tunnel experiment performed by Bezpalcova (2007). In this case, the results are focused on the measurement located downwind the first row of containers in order to reduce the influence of the inlet boundary conditions. For all the locations studied, the mean streamwise velocity ($\overline{U}$) is generally well predicted by LES and RANS (Figure 2, left panels). However, mean vertical velocity ($\overline{W}$) is underpredicted by, being LES that provides a better prediction (Figure 2, right panels). The underprediction of the vertical velocity is a common feature for RANS CFD models, as also observed by Olesen et al. (2008).

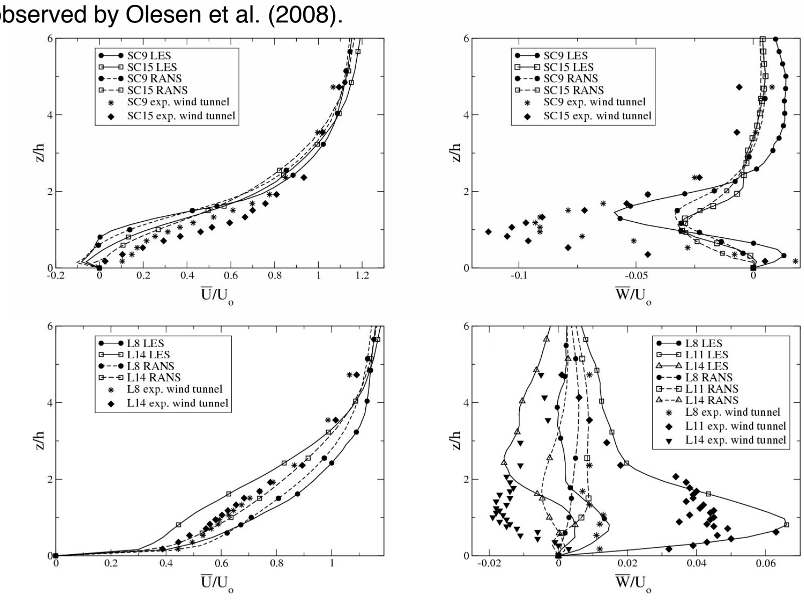

Figure 2. Vertical profiles of U and W at SC and L locations (see Figure 1 and 3).

3.2. Effects of geometry irregularities on local flow properties and on spatial average flow properties

Figure 3 shows LES isocontours of the mean streamwise velocity for the regular and irregular case at z/h = 0.5. In the regular case, repeated flow patterns are observed along the streamwise direction after the third canyon. When considering the irregular array, the repeated flow patterns are disturbed by the geometrical irregularities producing large local differences. Similar results are obtained by RANS simulations. These irregularities make the profile of $\overline{W}$ velocity component to vary in shape depending on the line location (see Figure2 right); not shown here, $\overline{W}$ exhibited a similar shape profile along the line L or SC in the regular case.

In the context of simplified urban canopy models, it is relevant to analyse the horizontal spatial average properties of the flow (Santiago et al., 2008). More details concerning the averaging technique can be found in Martilli and Santiago (2007). Results for the regular and irregular arrays from RANS and LES simulations are compared in order to study the differences in terms of global properties of the flow. The vertical profiles of $<\overline{U}>$ and $<\overline{W}>$ (Figure 4) shows that the effect of the irregularities of the geometry on the spatially averaged variables is practically negligible.

Figure 3. LES isocontours of mean streamwise velocity for regular and irregular configuration.

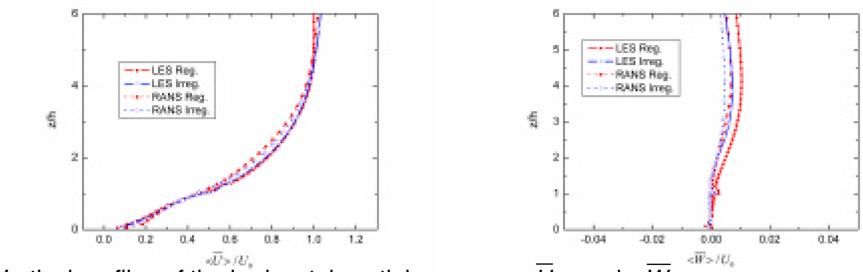

Figure 4. Vertical profiles of the horizontal spatial average $<\overline{U}>$ and $<\overline{W}>$.

4. CASE 2: INCIDENT FLOW OBLIQUE TO THE ARRAY

In this case one trial (trial 2682353, see Biltoft, 2001) of the field experiment was chosen for the LES and RANS simulations. The corresponding mean wind direction angle is of - 48º. In the experiment the wind direction slightly changes with time and with height. Here, we considered different values of the incident wind direction angle, α_0, that covers a similar range of the small time and height deviations of the incident wind direction angle reported in the sample measurements, i.e. - 42º<α_0<- 48º. This is aimed to get some insight on the influence of small upwind mast angle deviations on the results obtained from LES and RANS. The location of the pollutant source is indicated on Figure 1 (the passive pollutant is released from the roof of the container).

4.1. Comparison against experimental data

The profiles of the mean pollutant concentration computed by LES and RANS are compared against field data at some locations in Figure 5. The comparison at the main tower (MT) and tower B (TB) are shown. A good overall qualitative agreement is obtained. Indeed, at all the tower locations, the simulations profiles exhibit a similar shape to the one given by the experimental data. It is worth to note here, that taking into account the standard deviation of the concentration in LES results (horizontal bars), the latter globally cover the range of RANS and experimental data in almost all cases. The RANS are closer than the LES to the measurements or vice versa, depending on the location. These discrepancies have a similar order of magnitude as the differences observed on the mean concentration profiles induced by a small change in the inlet wind direction.

4.2. Effects on plume deflection of small changes of incident wind direction

In an urban environment the plume deviation depends on several factors such as the geometry of obstacles, the aspect ratio of the streets, the locations of the point sources etc., so that the plume spread is strongly influenced by the complex flow patterns inside the urban canopy. In particular, the flow close to the ground (not shown here) is strongly channelled along the street direction. As illustrated in Figure 6a for RANS, this effect makes the plume direction to be highly deflected from the incident wind direction in the close ground region. Moving to higher altitudes, above the obstacles array, the plume and incident wind directions tend to be aligned. Figure 6b exhibits the plume directions for an identical release source of pollutant as Figure 6a, but located at the ground level. It is shown that the differences of the plume direction between the incident angles - 42º and - 48º at the plane z/h=0.1 are even smaller for the source located at the ground. In the ground region the plume direction is almost parallel to the street. LES give similar results (not shown here) as RANS.

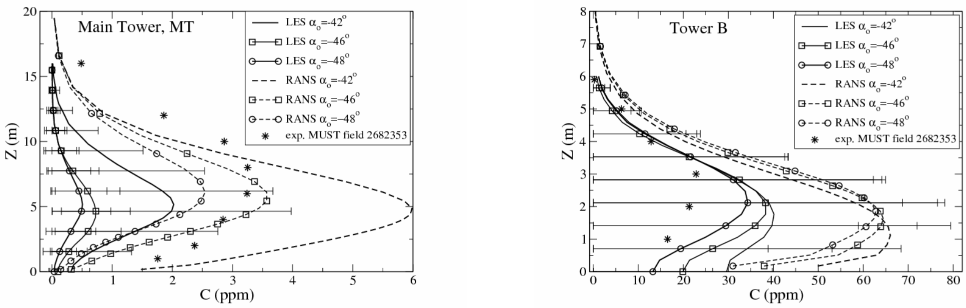

Figure 5. Mean concentration vertical profiles for several incident wind directions.

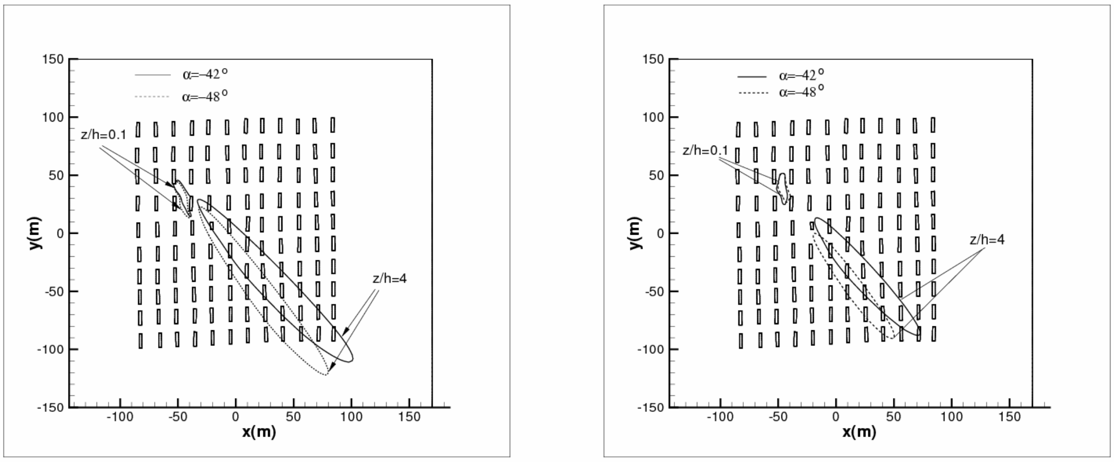

Figure 6. Pollutant concentration isolines at the horizontal planes z/h=0.1 and 4 and the two incident wind angles - 42° and - 48° for RANS simulations with the source release a) above the roof and b) at the ground level between two containers. Isolines correspond to 50% of the maximum in each plane.

5. CONCLUSIONS

The simulations are in a reasonable agreement with the experiment. For the present configuration and implementation LES and RANS provide similar results, the LES providing a better prediction of the local mean vertical-velocity component. It was shown that small geometry irregularities effects are important regarding local mean flow properties but are negligible regarding horizontal spatial average flow properties. For the range of incident wind direction angles considered, the plume dispersion is shown to be strongly affected by the channelling effect close to the ground region so that the plume is very little dependent on incident wind direction in this zone.

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