EVALUATION OF A GENERAL CFD-SOLVER FOR A MICRO-SCALE URBAN FLOW

Jarkko Saloranta and Antti Hellsten
Helsinki University of Technology, Laboratory of Aerodynamics, Finland

INTRODUCTION

In this work we study turbulent flow and pollutant dispersion in a simplified urban environment by means of computational fluid dynamics (CFD). The CFD-computations of the MUST case (Mock Urban Setting Test) carried out in this work are done in the framework of COST action 732. The CFD-code used in this work is a general versatile flow-solver called FINFLO (*Siikonen* 1995). It has originally been developed in the Laboratory of Aerodynamics at Helsinki University of Technology. FINFLO is a finite-volume based Navier-Stokes solver, it is formulated for structured multi-block grids and it can be efficiently run in parallel. So far, it has been applied almost exclusively to Reynolds-averaged Navier-Stokes simulations (RANS) of various engineering problems. However, it is in our interest to broaden the applicability of the FINFLO-solver also to environmental flows and dispersion related problems. A four-year project focusing on a problems similar to the MUST case has been started in our laboratory. In that project, we study the turbulent flow and pollutant dispersion in urban environment by means of large-eddy simulation (LES) and hybrid RANS-LES methods.

The MUST field-measurement campaign was a near full-scale experiment of a flow in an urban environment, that was conducted in Utah's West Desert area in 2001 (*Biltoft* 2001). There were 119 shipping containers plus one observation vehicle placed in an almost regular array of 12 x 10. The flow- and tracer-gas fields were measured for various wind directions and tracer release locations. Various wind-tunnel experiments of the MUST case have been carried out during the past few years, see e.g. (*Bezpalcova and Harms* 2005, *Gailis* 2004).

The MUST case is currently being employed as a modelling-quality-assurance exercise within the COST action 732 “Quality assurance and improvement of micro-scale meteorological models”. Our aim is to follow the systematic quality assurance practices proposed in the COST-732. Although the quality-assurance procedure addresses many aspects of the simulation model, the focus of this paper is subjected towards the grid convergence.

In these simulations the RANS-approach (Reynolds-averaged Navier-Stokes) is used to obtain steady-state solutions. Two turbulence models are used: the *k-w SST* model (*Menter* 1994) and a model close to the standard *k-e* model (*Launder and Spalding* 1974). The dispersive tracer gas is modelled as a passive scalar and the wall-function approach is employed to compute the viscous fluxes at solid surfaces. Simulations are performed for two different wind directions: for 0° and 45° wind directions. For the 0° case, only the flow field is computed, but for the 45° case the concentration field is also computed. All simulations discussed in this paper are in wind-tunnel scale and the obtained flow-field results are compared to wind-tunnel results from (*Bezpalcova and Harms* 2005). The main objectives of this work are to find out if our in-house code FINFLO is suitable for urban flow and dispersion simulations, to gain experience on simulations of urban micro-scale problems within our research group, and to assess the quality assurance practices constructed in the COST-732.

SIMULATION METHOD

In this section we briefly discuss the applied simulation methods used in this work. This includes the turbulence models used, definition of the computational domain and grid, the boundary conditions applied and the overall solution method of the governing RANS-equations.

Turbulence models

The *k-w SST* (*Menter* 1994) was our first choice for the turbulence model. However, in this case no stationary result was achieved and the results oscillated around some mean value. Therefore we decided to switch to the standard *k-e* model (*Launder and Spalding* 1974), which is very popular in this kind of simulations. Since the *k-e* model is not readily implemented in FINFLO, we modified the *k-w* model to very closely resemble the standard *k-e* model by introducing a cross-gradient term in the *w*-equation and by adjusting the model coefficients, see (*Menter*, 1994). We refer this model to as the *k-w/e* model. When the *k-w/e* model was used the oscillations dissipated and steady state results was achieved. All the results presented in this paper are computed using the *k-w/e* model. A simple gradient-diffusion model is used for the turbulent concentration flux. The turbulent diffusivity of concentration is approximated as ν_T/s with the value of 0.8 given for the Schmidt number s.

Solution domain and grid

The container height *H* is used as reference length in this work. The computational domain extends 23.8*H* upstream from the most upstream obstacles, 33.3*H* downstream from the most downstream obstacles, *7.3H* upwards from the container roof level and about 21.4*H* at both sides from the obstacles (see Figure 3). Coordinate *x* is always aligned to inflow wind direction, *y* is normal to wind direction and parallel to ground surface and *z* is normal to ground surface. The velocity components *u,v* and *w* are respectively defined.

On the finest grid level (level 1) the grid has about 3.6 million control volumes (CV) and it is divided to 265 blocks. The grid is made so that there are 12 CV across the container height *H*, 8 CV across the container width *W* and 24 CV along the container length *L*. There are 12 CV across the narrower streets and 16 CV across the wider streets. On top of the containers, there are 16 layers of CV. The coarser grids (level 2 and level 3) are obtained by using every second and every fourth grid lines respectively from the finest level grid.

Boundary conditions

The inflow boundary conditions to the computational domain are defined as follows. The velocity profile is assumed to obey the logarithmic law for a fully rough surface. This log-law can be written as

$$\frac{u}{U_{ref}}(z) = \frac{u^*}{U_{ref}}\left[\frac{1}{k}\ln\left(\frac{z}{k_s}\right) + 8.5\right] . \quad (1)$$

For the MUST case the effective roughness is k_s=0.55m. Equation (1) is fitted to the wind tunnel data and the value u^*/U_{ref} =0.0675 gives the best fit. The reference velocity U_{ref} is defined as the mean velocity of the inflow profile at z=7.29m. For the turbulence quantities at the inlet boundary, a constant turbulent kinetic energy $k=(u^*)^2/C_\mu^{1/2}$ is given and the turbulent viscosity n_T is set as $n_T(z)= ku^*z$. Here k=0.41 and C_μ=0.09.

The ground and the containers are modelled as smooth surfaces, because we are simulating wind-tunnel conditions, and the wind-tunnel model surfaces are smooth. The outlet boundaries and the top boundary are defined as follows. The ambient pressure is given and all other flow variables are extrapolated. In the extrapolation of the flow variables a constant gradient is assumed. In the 0° simulation the side walls are also assumed to be solid, as we are computing a wind-tunnel case. We use the same grid for the 45° case also, so the wind-tunnel walls are not present in those simulations.

Solution method

FINFLO is a block-structured cell-centered finite-volume method based flow solver. It has originally been developed for compressible aeronautical applications, but the latest version can also be applied to incompressible flows (artificial compressibility method). In the present computations the flow is assumed compressible, since the verification of the incompressible code is still undergoing. The Mach number used in this work is 0.2, at which the compressibility effects are assumed to be neglilible.

The stationary solution is achieved by a McCormack type implicit solution of the governing RANS-equations and multigrid-method is used to speed up the convergence towards the steady state. A second-order upwind biased interpolation scheme is used for the inviscid fluxes. For the viscous terms, a second-order thin-layer algorithm is applied. A detailed description of the solution method used in FINFLO can found for example in reference (*Siikonen* 1995).

The wall-function approach (WFA) is applied to the viscous fluxes at solid surfaces in this work. The WFA was not employed in FINFLO previously, and was thus implemented for this case. It was verified by using some simple test cases such as flat-plate boundary layer and flow in a rectangular duct. Different block arrangements and grid orientations were used to check the correct behaviour. The WFA used in this work is based on (*Launder and Spalding* 1974).

RESULTS

In this section we present some results for the 0° and 45° cases. The velocity plots shown in this paper are made nondimensional with the reference velocity U_{ref} described earlier in this paper. The nondimensional concentration C^* presented for the 45° case is defined as

$$C^* = \frac{CH^2U_{ref}}{Q} \quad , \quad (2)$$

where C is the computed concentration, H the container height and Q is the total tracer release rate [m^3/s]. The measured data used as a reference in this paper is from a wind-tunnel experiment by Bezpalcova and Harms (2005).

Wind direction 0°

The computed profiles for the velocity u/U_{ref} for all three grid resolutions are shown in Figure 1. Owing to space limitations only two different positions 7 and 14 (see Figure 3) are shown. From Figure 1 we can see the ambiguous behaviour of the results in the context of grid convergence. The qualitatively best results are obtained at the grid level 2 or even at the grid level 3, as it is seen on the left- and right hand side profiles, respectively. The left hand side profiles clearly indicate that the grid resolution is not on asymptotic range and thus we are still far from the grid-independent RANS-result. The present results are in most parts of the domain far from the measured data, which is partly owing to the inadequate grid resolution. In addition, one should also remember that the RANS-approach is not necessarily adequate in this kind of flow, since turbulence around the buildings is far from any equilibrium. The WFA approach may also be questioned for the same reason.

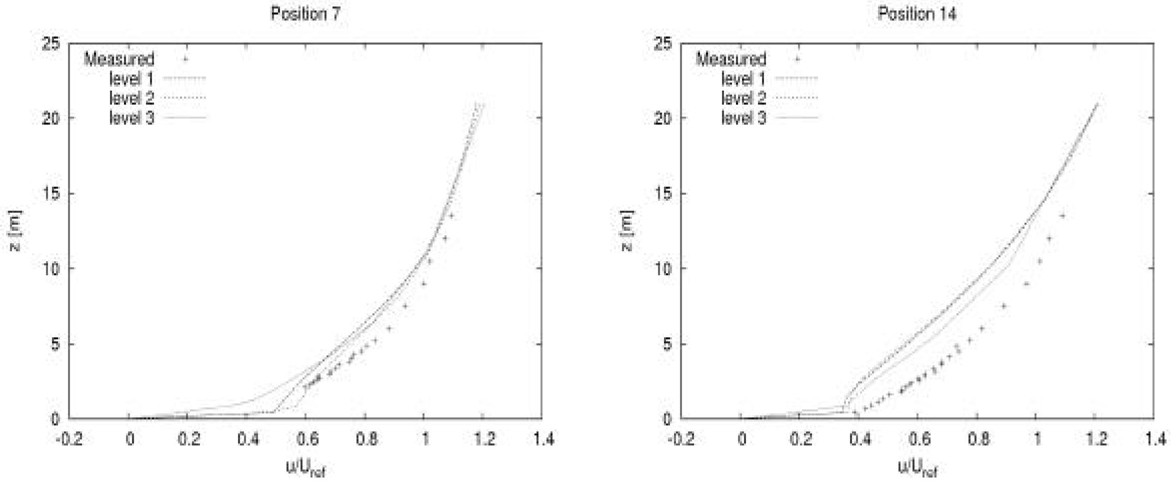

Fig. 1; The u/U_{ref} velocity profiles at two different positions from the 0° case.

Wind direction 45°

In Figure 2 is shown the computed profiles for the velocity u/U_{ref} at two different positions 49 and 51 (see Figure 3) for all three grid resolutions. We can see that the grid convergence of the velocity component u in the 45° case is a lot more evident than it was in the 0° case. The computed results have less variations between grid levels. But especially in range of $z=0...5$m the present results a still far from the reference results.

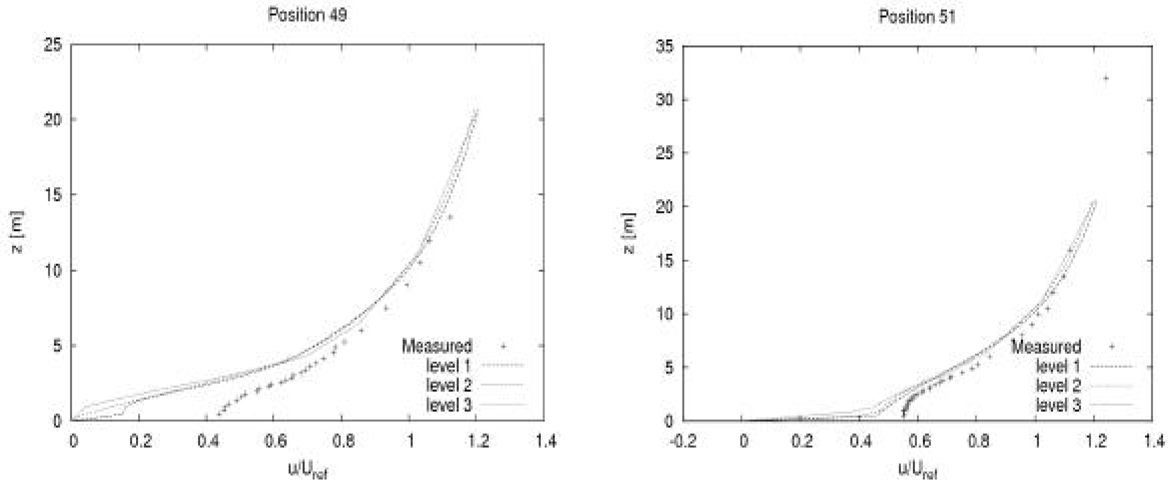

Fig. 2; The u/Uref velocity profiles at two different positions from the 45° case.

The source for the tracer is located in the middle of the first wider street between the second containers at level $z=1.8$m (see Figure 3). In Figure 3 are presented the distributions for the scaled concentration C^* along two lines that are at level $z=1.8$m and their location in xy-plane can be seen in the right hand side of Figure 3. The first line is located along a wider street and the other along a narrower street. As the profiles for the velocity component u showed somewhat consistent grid convergence behaviour in Figure 2, the dispersion distributions fail to do so. Again, this is a clear indication of the inadequate grid resolution. In the right hand side of Figure 3, the dispersion distribution at level z ˜ 1.0m is also shown, and we can see how the tracer distribution becomes strongly asymmetric owing to the advection along the wider street canyons.

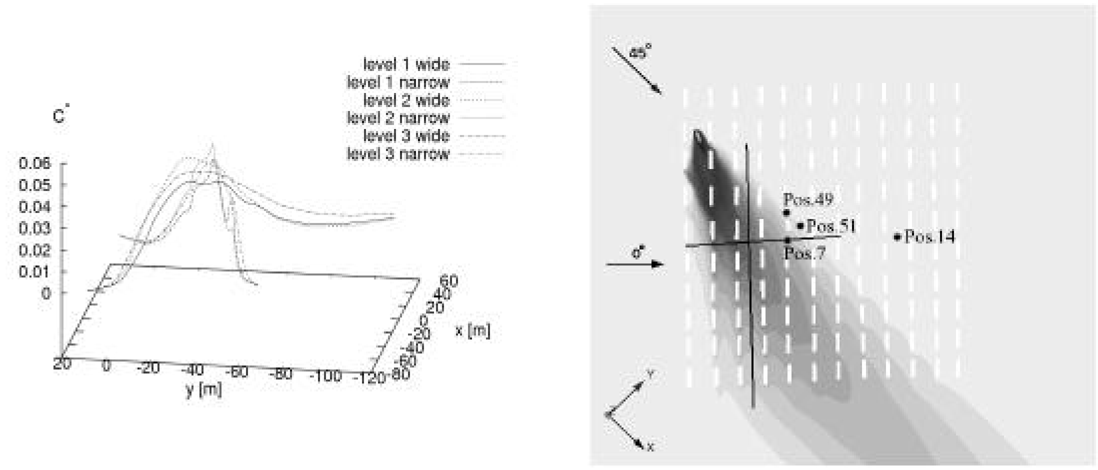

Fig. 3; On the left hand side: the concentration C distributions. On the right hand side: positions of the velocity profiles and the concentration plot lines and the dispersion distribution near the ground.*

CONCLUSIONS

This work is carried out for three principal reasons: to find out if our in-house code FINFLO is suitable for urban flow and dispersion simulations, to gain first-hand experience of micro-scale urban-flow simulations, and to demonstrate a systematic quality-assurance procedure for the simulation model according to the guidelines constructed in the COST–732. Because the quality assurance procedure is a broad subject, only the grid-convergence aspect is focused in this paper. Although, slight modifications to the solver-code were needed, FINFLO was found to be capable of such urban micro-scale simulations. Grid convergence is clearly not achieved with the current grid consisting of 3.6 million CV. When looking at the flow field results, the grid convergence of the 45° wind direction case is more coherent than that of the 0° case. But for the dispersion results, a proper grid convergence is again not achieved. Thus the 3.6 million CV grid is not sufficient for a grid-independent RANS result for a such flow case as MUST. This might imply that the computational cost of a grid-independent RANS-result may become so high that large-eddy simulation of a flow problem such as MUST becomes a feasible alternative to RANS.

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