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LES STUDY OF UNSTEADY FLOW PHENOMENA IN AN URBAN GEOMETRY – THE NEED FOR SPECIAL EVALUATION METHODS

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Abstract: Large Eddy Simulation (LES) is performed in the semi-idealized “Michel-Stadt” urban geometry. LES results are successfully compared with detailed experimental data from the CEDVAL-LES wind-tunnel database. Examination of the time-evolution of flow and vorticity fields reveals interesting turbulent phenomena like gusts, unsteady vortices, non-Gaussian velocity distributions and the creation of coherent structures. This study contributes to the need of investigating ways of analyzing the LES results.

Key words: *CFD, Large Eddy Simulation, validation, turbulent urban flow, coherent structures, wind tunnel, ADREA*

INTRODUCTION

Computational Fluid Dynamics (CFD) is one of the most valuable and versatile approaches for urban pollution and air quality studies. The LES methodology, even if it is currently not widely used for regulatory purposes due to its high computational cost, is expected to play a major role in atmospheric dispersion modelling. Compared to the more widespread Reynolds Averaged Navier-Stokes (RANS) approach, LES partially resolves turbulence and can provide concurrent time series of the desired variables at all points of the flow field and not just average values like RANS. With LES we can examine the unsteady dynamics of the flow and contribute to a deeper understanding of driving physical mechanisms and of fundamental turbulent flow regimes. The amount of simulation data from an LES can be huge and needs additional and different methods to be evaluated and analyzed.

A further issue is the comparison of LES with experimental data. The availability of time series makes the calculation of statistics, high order moments and correlations possible, providing additional information for evaluation (Hertwig, 2013). Thus there is a need for specifically designed and well documented experimental datasets that can significantly help in validating and improving LES models, like those of the CEDVAL-LES wind-tunnel database of the University of Hamburg. In the current study, the semi-idealized city “Michel-Stadt” was chosen, which mimics typical central-European cities at a scale of 1:225 (Figure 1). The geometry is composed of 60 differently shaped building blocks with courtyards and various roof heights of 15, 18 and 24 m, covering an area of 1320 m x 830 m at full scale. The atmospheric boundary layer of the approach flow is characterised by a roughness length z_0 = 1.53 m and a power law profile with exponent α = 0.27 for a reference velocity of 6.1 m/s at 100 m height. Thousands of Laser Doppler Anemometry (LDA) measurements are available at 40 vertical profiles and at 5 horizontal levels in the central part of the city (at heights of 2, 9, 18, 27 and 30 m).

METHODOLOGY

The LES model of the ADREA-HF code is used for the simulations. The equations solved and an evaluation of the implemented methodology are discussed in Koutsourakis et al. (2010, 2012).

A domain of 1670 m x 900 m x 147 m in x, y, z directions is used, discretized with a mesh of 419 x 238 x 30 cells. The resolution of 3 x 3 x 3 meters that is achieved in most parts of the city is not very high, but is considered adequate for performing urban LES (Tominaga et al., 2008). Rough wall functions are used with a roughness length of 0.0625 m inside the city (for ground and buildings) and 1.5 m upwind (ground). The domain is laterally bounded by smooth walls. At the inlet and top a Langevin-type boundary condition for the velocity U is applied, fixing U_{mean}, variance σ_U and autocorrelation time scale T_U to the experimental values. The Smagorinsky model with constant $C_s = 0.1$ and a van Driest-type damping near the wall is used for the sub-grid scale modelling. The bounded central differences numerical scheme is chosen for the discretization of the convective terms and for the time advancement the second-order accurate Crank-Nicolson method is used. The time step is limited to 0.2 s. A total of 10000 s is simulated, of which the first 900 s are not considered for the statistical analysis. 8844 "sensors" that provide time-series are placed at various locations. The current simulation is significantly improved compared to that of Koutsourakis et al. (2012), having a finer grid and using a different numerical scheme. The computational time is about 39 days on a quad-core personal computer. More information about the simulations can be found in Koutsourakis (2014).

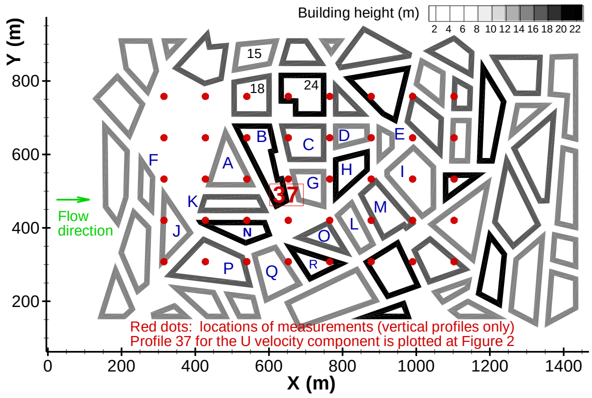


Figure 1. The Michel-Stadt city with building heights

RESULTS AND DISCUSSION

Mean flow comparison with experimental data

The scatter plot of experimental vs. simulated results for the mean velocity component U_{mean} at all 2158 measurement locations and an indicative vertical U_{mean} profile are presented in Figure 2.

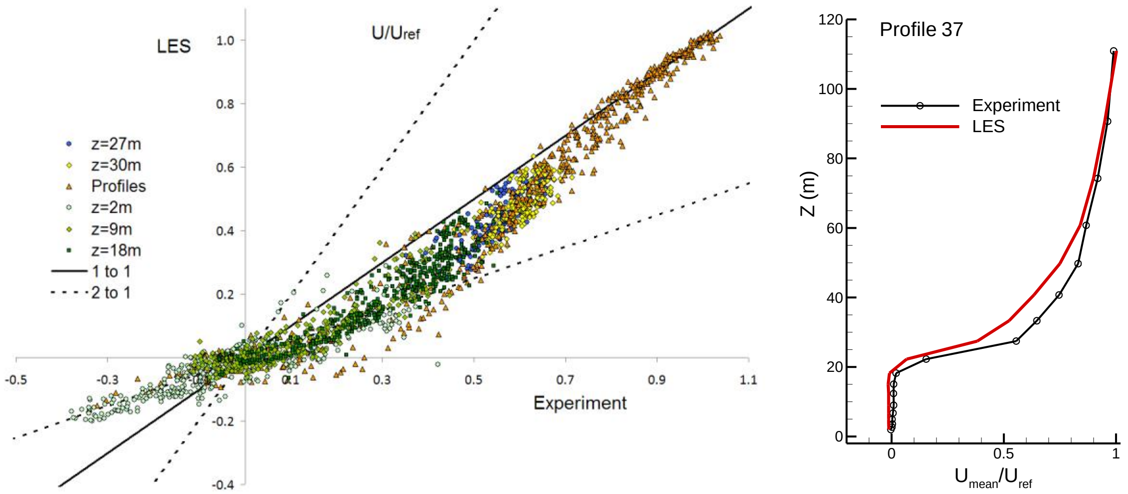


Figure 2. Left: Comparison of experimental and LES values of mean velocity U_{mean} at all measurement points. Right: Vertical velocity profiles of experiment and LES at point 37, between buildings **B** and **G** (Figure 1)

Qualitatively, the average flow results are good, since most of the points fall well within the dotted lines that indicate a 1-to-2 and 2-to-1 relation and the calculated profiles follow closely the experimental ones. An easily observed underestimation of the mean velocity at medium heights is due to the much higher underestimation of the stresses at those heights. Another issue is the lower velocities of LES very close to the ground that can be seen at the scatter plot. It is noted that preliminary results with a finer grid show significant improvement. As a first attempt to quantify that, statistical indexes (validation metrics) can be used. Table 1 presents FAC2 and HR as defined in Hertwig et al. (2012) for the vertical profiles (that represent the overall quality of the LES) and two horizontal planes at 2 m and 30 m for 3 meshes. Even though the statistical indexes can be misleading and should not be interpreted without inspection of the flow field, the tendency of improvement is unambiguous as the grids get denser.

Table 1. Validation metrics for U_{mean}/U_{ref} & V_{mean}/U_{ref} for 3 meshes: coarse of 0.74 million cells (minimum horizontal resolution of 6.6 meters)/ **current** (3 million cells, 3 m resolution)/ finer (7 million cells, 2 m resolution)

	Vertical profiles		**z = 2 m**		**z = 30 m**	
Mesh \Variable:	U_{mean}/U_{ref}	V_{mean}/U_{ref}	U_{mean}/U_{ref}	V_{mean}/U_{ref}	U_{mean}/U_{ref}	V_{mean}/U_{ref}
Coarse (FAC2 - *HR*)	0.74 - *0.61*	0.63 - *0.62*	0.16 - *0.08*	0.31 - *0.21*	1.00 - *0.47*	0.71 - *0.75*
Current (FAC2 - *HR*)	0.77 - *0.66*	0.66 - *0.66*	0.44 - *0.16*	0.45 - *0.25*	1.00 - *0.75*	0.79 - *0.85*
Finer (FAC2 - *HR*)	0.85 - *0.71*	0.74 - *0.74*	0.62 - *0.30*	0.54 - *0.31*	1.00 - *0.96*	0.87 - *0.91*

Unsteady turbulent phenomena and coherent structures

With LES successive instantaneous flow snapshots can be studied, revealing turbulent features known from the experiments, like unsteady flow characteristics and non-Gaussian velocity distributions. Figure 3 presents two snapshots of the horizontal velocity vectors at the sensors' positions in the z = 2 m plane.

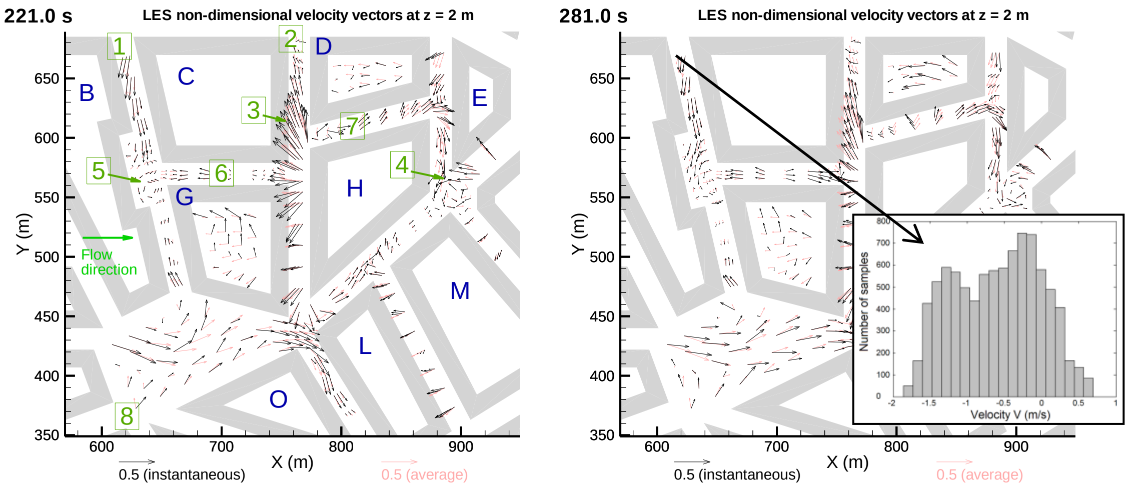
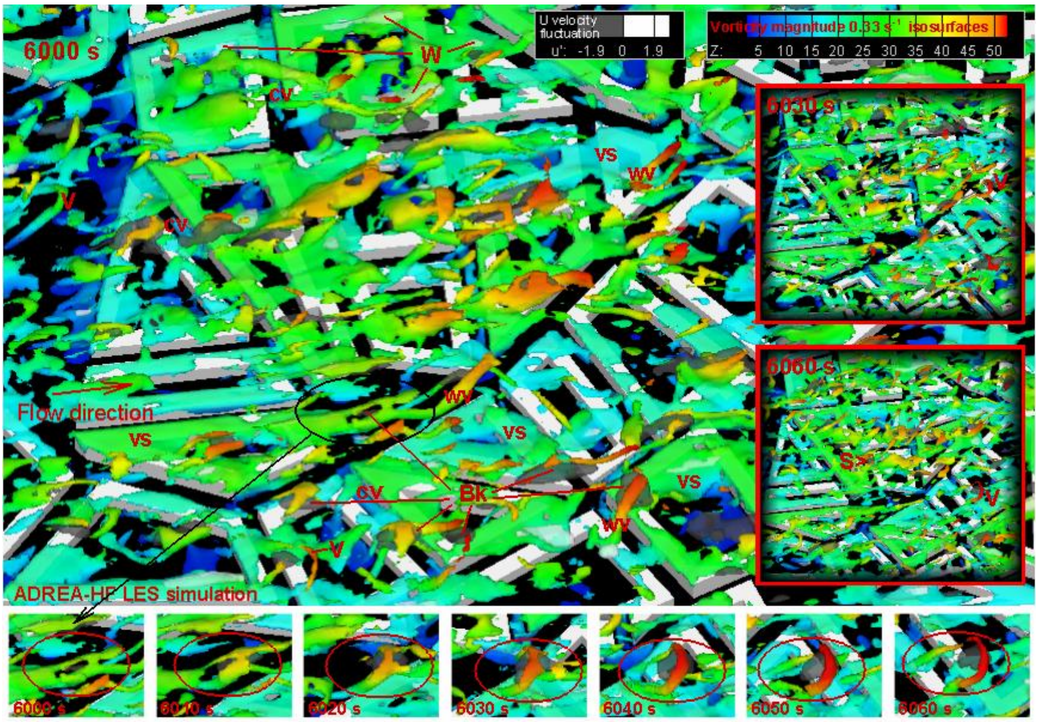


Figure 3. Two frames of a 9000 s video showing the LES instantaneous velocity vectors at z = 2 m. In the inset the probability density function of the *V* velocity at point 1 is plotted, which shows bimodal behaviour

The observation of the video can lead to numerous remarks. At point **1** a recirculation with unsteady limit exists as the flow turns into the canyon passing around the corner of building **B**. The leftmost vector at point **1** is either inside the recirculation, having a very low velocity, or outside of it, having a significantly higher velocity. The velocity distribution of the *V* component can be seen in the inset of Figure 3 and is bimodal. The two physically possible flow states are represented from the peaks, while the mean value does not really have a physical meaning. In this case neither a RANS simulation nor the use of validation metrics like FAC2 and HR are rigidly correct. With the use of LES, other ways of comparison should also be chosen, like the instantaneous flow events or the distributions of the variables. The ability of LES to calculate non-Gaussian behaviour is crucial for the correct prediction of the flow, as mentioned in a previous study (Hertwig et al., 2012).

At points **2** and **3** gusts can be frequently observed. At point **4** a persistent vortex that slightly shifts at high frequency around a central position of the crossroads is present in both the CFD and the experiment. Around this vortex there are (both in the wind tunnel and the LES) a lot of points featuring skewed or bimodal behaviour for the velocity distributions. The occasional vortex at point **5,** however, is very unstable and much weaker. Around point **6** an oscillatory moving end of the recirculation behind the building **B** exists. Even if the general flow characteristics are captured by the LES in this case, both FAC2 and HR in this area are very low, most probably due to the slightly different position of the recirculation end compared to the experiment. At point **7** LES also predicts a recirculation (easily seen in 3-D plots of stream traces), which could not be identified in the experiment in this case. Despite this, FAC2 for the *V* component is very high in this area. In the cases of points **6** and **7** the validation metrics are misleading. Very high frequency changes of flow direction and a strong velocity variability can be noticed in the yards of buildings **D** and **G** in both the LES and the experiment. At point **8**, the *average* vectors of LES and experiment have significantly different directions. This could lead to the conclusion that the simulation completely failed here. However, studying the instantaneous flow fields reveals that occasionally the direction changes to that of the experiment. Unfortunately no experimental values exist below that point, in order to help in investigating reasons for the different behaviour. The analysis made clear that more measurement points around the main-interest area would have been helpful in order to have a better understanding of the flow features. It is obvious that a cooperation of experimental and LES research teams both before and after the experiments is of benefit for all parties.

The study of coherent structures that can be identified from the LES is very revealing when it comes to a more fundamental understanding of flow dynamics. In Figure 4 the 0.33 s^{-1} vorticity isosurfaces are presented at the central part of the city, colour-coded by the z-axis height. Instantaneous low-momentum (of negative velocity fluctuation *u′*) areas are also plotted as black isosurfaces (Bk) and high-momentum as white (W). We can determine for example structures like in-canyon cylindrical vortices (cv), vorticity sheets (vs) that usually shed-off the building roofs, worm-like vortices (wv) that are usually one of the two legs of hairpin vortices (V), which in turn correlate with low-momentum areas.



igure 4. Snapshots of vorticity and velocity-fluctuation isosurfaces revealing coherent structures.

By studying the time-evolution of the structures (top part of Figure 4 presents the same area at 3 different times), conclusions about their dynamic behaviour can be drawn. As an example, the bottom part of Figure 4 shows the creation of a hairpin vortex: At first, the vorticity sheet is perforated by an upward-moving low-momentum fluid area which occured just below it (6000 s). This creates two longitudinal vortices at the sides of the hole (6000-6010 s). The vortices are transported by the flow in parallel to their mutual lifting and joining (6020-6030 s). This leads to their characteristic hairpin shape (6040-6060 s). By studying the relevant video, many such events can be identified. At the video the creation of a hairpin vortex from another one can also be seen, when the low-momentum area below it elongates and breaks, like in point **S**. Similar events are reported in the literature (e.g. Adrian, 2007). It is known that low-momentum areas have a correlation with pollutant removal events (Coceal et al., 2007). High-momentum (white) isosurfaces are seen to correlate with vorticity sheets and also with the hairpins.

Ways to account for the time-dependent nature of LES in validation studies are discussed by Hertwig (2013). The application of more sophisticated measures of simulation quality not only helps to understand the physical accuracy of the simulation, but can also be of guidance to disentangle errors and sources of uncertainty in the modelling. Apart from comparisons based on higher order statistics and frequency distributions, eddy statistics (e.g. in terms of auto- or two-point correlations, integral length scales or spectral properties of the flow) and conditional averaging should also be consulted to gain further insight into the simulation quality. Depending on the spatial-temporal resolution of the reference experiment, other advanced analysis methods like proper orthogonal decomposition, stochastic estimation or wavelet transform methods can be used comparatively as well (e.g. Hertwig et al., 2011; Kellnerova et al., 2011; Hertwig, 2013). A close collaboration between LES and experimental communities, will help in that objective.

CONCLUSIONS

LES has a strong potential and can not only provide a general picture of fluid motion in complex geometries, but also supply information about unsteady flow dynamics. With appropriate post-processing, like the time-dependent flow visualizations presented here, LES contributes to a more fundamental understanding of turbulent flow phenomena. This work also makes clear that there is a need to identify and standardize methods to analyze LES results and to compare them with reference data, since classic ways can be misleading. Such methods could include processing the time-series, observing the time-evolution of vectors or isosurfaces and investigating the position, strength and frequency of particular flow events. This study also reveals the need of parallel work of experimentalists and modellers, in both the design of the experiments and the interpretation of the model results. The hope is that in the future, along with the modelling guidelines and the LES-oriented post-processing practices, more sophisticated quality assurance methodologies particularly suitable for turbulence-resolving simulations will emerge.

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