17th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 May 2016, Budapest, Hungary

SIMULATING TURBULENT AIR FLOWS IN CENTRAL LONDON AND STUDYING EFFECT OF TALL BUILDINGS

Elsa Aristodemou [1,2], Luz Maria Boganegra[1], Christopher Pain[2], and Alan Robins [3]

[1] School of Engineering, London South Bank University, London, UK.
[2] Department of Earth Sciences, Imperial College London, London, UK.
[3] Department of Mechanical Engineering Sciences, University of Surrey, Surrey, UK

Abstract:

We present work associated with the implementation of a validated street-canyon/neighbourhood model that can help assess the air quality within existing building and neighbourhood designs and suggest modifications & improvements in order to produce sustainable, safer, healthier, and more comfortable urban environments. The work was motivated by both the increasing number of tall buildings in central London ("skyscrapers") and also the recent plans of placing combined heat and power plants (CHPs) within the urban environment. The Large Eddy Simulation (LES) work was initiated after a series of wind tunnel experiments were carried out at the Enflo wind tunnel (University of Surrey) in order to assess the effect of emissions from Combined and Heat Power plants (CHPs) on top of one of the buildings. A series of scenarios were tested in the wind tunnel and mean concentrations and their fluctuations were measured. The LES models were set-up representing the wind tunnel geometries as well as wind conditions. The novel LES methodology implemented uses an unstructured, adaptive mesh and an anisotropic eddy viscosity tensor for the sub-grid scales (based on the anisotropic mesh). The comparisons of the complex turbulent air flows and concentrations between model results and wind tunnel data show a good correlation – less than 20% error between predictions and measured data. We also looked at the effect of tall buildings on the surrounding complex air flows and dispersion of pollutants, using as prime examples the "Walkie-Talkie" building and the Shard skyscraper in central London, UK. Interesting simulation air flow results and dispersion for the "Walkie-Talkie" building are presented.

Key words: *air pollution, urban environment, wind tunnel experiments.*

INTRODUCTION

The need for the development and support of accurate urban dispersion models as well as monitoring air quality is widely recognised worldwide. Efficient, fast, and accurate urban dispersion predictions are necessary to assist with improving air quality within the urban environment through optimisation of critical infrastructure and control of emissions. Correct abatement policies require the understanding of the interaction of pollution from different emission sources at different scales, in a turbulent environment. Appropriate air pollution models involve the solution of non-linear equations (advective transport, chemical reactions, and turbulent diffusion) and require accurate predictions of spatial concentration gradients, as these affect both the reaction rates as well as the transport of the pollutants. To achieve this fine/high-resolution spatial grids are necessary; this has been a major issue in the last four decades, with adaptive grid methodologies appearing in the early 1990s by Benson and McRae (1991) resulting in the development of their Dynamic Solution Adaptive Grid Algorithm (DSAGA) on structured grids whilst Tomlin et al. (1997) and Ghorai et al. (2000) were amongst the first to implement an adaptive grid approach on unstructured grids for pollution problems. High-resolution grids are necessary in determining the correct turbulent characteristics of the flow field and understanding the mixing processes and scalar exchange within and above canyons is also crucial in obtaining accurate predictions of the concentration levels (Zhoun and Hanna, 2007; Solazzo and Britter 2007). Turbulent flows in air pollution problems have traditionally been dealt with the Reynolds-Averaged Navier-Stokes methodology (RANS), and the well-established k-epsilon turbulence model. However, studies by Coirier et al. (2005) and Di Sabatino et al. (2008) amongst many showed that the turbulent kinetic energy was usually under-predicted and hence determining the correct turbulent parameters in the k−epsilon turbulent model was a priority – more so perhaps than grid refinement for obtaining accurate turbulent flow predictions. One of the principle concerns in street canyon pollution studies is the transfer of pollutants from within the canyons to the external shear layer at the top of the canyon. Numerical studies by Baik and Kim (2002) and Caton et al. (2003) showed that both the vertical turbulent velocities and the vertical mean velocities are important. The effect of the turbulent intensity conditions at the inlet on the dispersion of the pollution within the street canyons is also discussed in Kim and Baik (2003), and Milliez and Carisimo (2007). These authors also highlight the importance of the turbulence model parameterisation chosen for their k-epsilon model (RANS) in the simulated mean concentrations and fluctuations and their variance.

An alternative and highly favoured and powerful approach to the well-established RANS models has been gaining momentum fast over the last decade – this being the large eddy simulation (LES) - facilitated by the rapid growth in computing capabilities (Walton and Cheng 2002; Baik and Kim 2002; Baker et al. 2004;). The strength of LES lies in the fact that, in contrast to both the DNS and the RANS approach, it is able to simulate the unsteadiness of the flow and capture the large-scale turbulent structures explicitly whilst the smaller-scale structures are modelled. Modelling the smaller structures requires some assumptions and parameterisations and the sub-grid scale model has been traditionally based on the well-known Smagorisnky-type eddy viscosity model (Smagorinsky, 1963) with subsequent modification and development of a variety of sub-grid scale models over the past three decades (Germano et al. 1991; Porte-Agel, 2004; Kleissl et al. 2006). Adaptive grids have also been implemented in conjunction with the LES method, with one of the earliest works being those of Ghorai et al. (2000) and Wissink et al. (2005). Fully three-dimensional dynamic grid adaptivity for air quality models is relatively new. Constantinescu et al. (2008) show that high resolution grids are needed both near the emission sources of pollution as well further upwind. Aristodemou et al. (2009) and Boganegra (2016) implemented and validated the adaptive LES method represented in this study using mean flows and fluctuations against wind tunnel data. We continue in this study the exploration of adaptive LES on unstructured grids for urban pollution problems for a new building configuration and investigate the correlation between simulated and measured (wind tunnel) mean concentration levels. We also implemented the LES method in the new area around the Walkie-Talkie building (London, UK) (Bernal-Castro, 2015) in order to study the effect of tall building and also look at the effect of the curved design on the developed flow patterns and effect on the dispersion of pollutants.

METHODOLOGY

Modelling realistic urban flows requires a compromise between the steady-state RANS method and the computationally-intensive direct numerical simulation (DNS) method (Coceal et al. 2007). This is achieved through the gaining popularity large eddy simulation (LES), especially when adaptive-meshes are employed (Pope, 2000). The methodology we implement was initially developed by Bentham (2004), and combines a Smagorinsky-type sub-grid-scale turbulence model, with a fully adaptive unstructured mesh that optimizes the numerical resolution (finite element sizes) throughout the flow. Transport of pollutant concentrations is determined by a high resolution method, which is globally high order accurate in space and time and is designed for use with unstructured finite element meshes (Pain et al., 2001). The advection scheme provides robustness and may even be used as a alternative to traditional LES models (e.g. providing additional dissipation) for the pollutant concentration or momentum fields. The model employs a world-leading anisotropic mesh adaptivity method based on mathematical optimization as described in Pain et al. (2001). This method adapts tetrahedral elements to resolve all flow variables, e.g. velocity, pressure, particle concentration, by producing long-thin (anisotropic) elements with large aspect ratios where the physics dictates, such as in boundary layers. This can achieve great computational efficiency for large transient 3-D fluid flow problems and is fully exploited in the computationally demanding urban flows modelled here. For large problems, a tetrahedral-based parallel adaptive-mesh method described in Gorman et al. (2003) is exploited to achieve highly detailed turbulence model results. With the non-uniform adaptive resolution and use of parallel computing, varying building scales can be resolved. Our methodology has been validated against wind tunnel data (Bentham, 2004; Aristodemou et al. 2009; Boganegra, 2016) as collected in the Enflo wind tunnel (Robins, personal communication). The

Enflo wind tunnel has been used successfully in many studies of atmospheric air flows and dispersion (Carpentieri and Robins, 2015; Belcher et al. 2015) and measurements from one of these experiments is being utilised in the current study.

The LES equations

The equations used are the three-dimensional filtered Navier Stokes equations for mass continuity and momentum, as follows:

(1) Mass Continuity $\frac{\partial \tilde{u}_i}{\partial x_i} = 0$

(2) Momentum $\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\upsilon\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) + \tau_{ij}\right]$

(3) Stress tensor components, τ_{ij}, through: $\frac{\partial \tau_{ij}}{\partial x_{ij}} = \frac{\partial}{\partial x_{ij}}\left[\nu_{jk}\frac{\partial u_j}{\partial x_k}\right]$ where

(4) Eddy viscosity mode is given by: $\nu_{ij} = (C_s\Delta)^2 \tilde{S}_{ij}$ and is dependent on the local filter width Δ – associated with the anisotropic adaptive mesh. Hence, a unique anisotropic eddy viscosity model is implemented, with the local strain tensor components being given by:

(5) The local strain rate tensor component : $\tilde{S}_{ij} = \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$

Wind tunnel Experiments

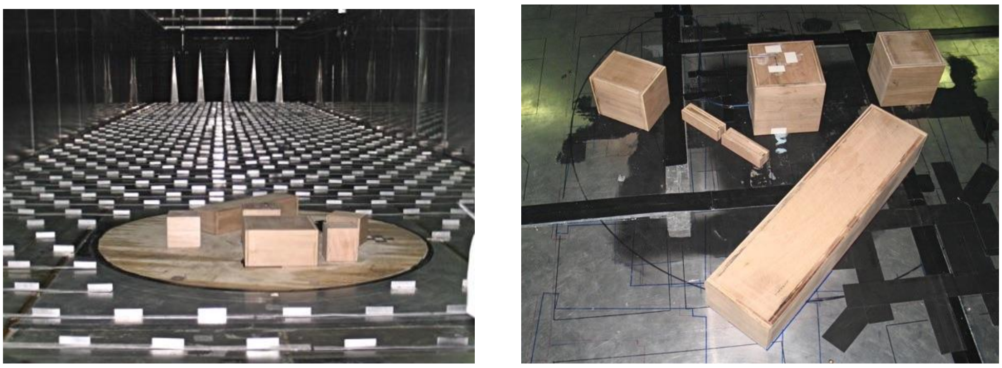


Figure 1 The complex building configuration in the Enflo wind tunnel, University of Surrey, UK.

The Enflo wind tunnel (University of Surrey) was used to carry out a number of studies with the complex building configuration of interest, as shown in Fig. 1. A total of eight cases were tested representing configurations in which some of the buildings were removed. In the work presented here, the "all-buildings" case was considered. Reference wind velocity was taken to be 2.1 m/s whilst, and mean concentrations and their fluctuations were measured. Four different source locations on top of one of the buildings, were considered (each representing a different tracer), and experiments were also run for four different wind directions.

COMPARISONS OF LES RESULTS WITH WIND TUNNEL DATA

The LES simulations were carried out on the Dell Precision Tower 7810 computer, with a dual Intel Xeon Processor, until a fully turbulent flow field was produced. The tracer dispersion results are shown in Figs 2 and 3, whilst comparisons with wind tunnel mean concentration values are shown in Fig 4, where a good correlation was found, with less than 20% error in some cases.

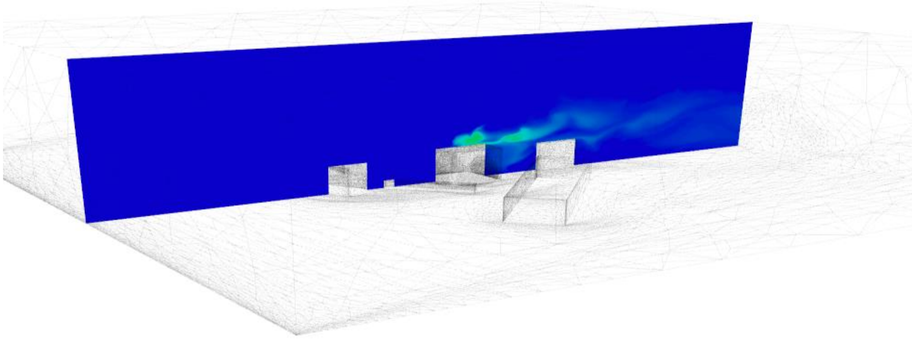
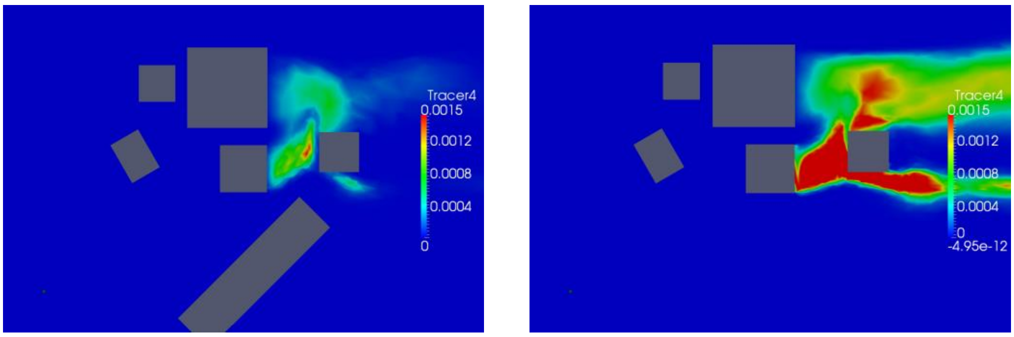


Figure 2 Vertical Cross-section through centre of computational domain for the dispersion of Tracer 4, with source at top of building.



(a) At Height H=0.05 m (b) At height H=1.2 m

Figure 3 Case 1: Horizontal views of tracer dispersion (tracer4) at two different heights.

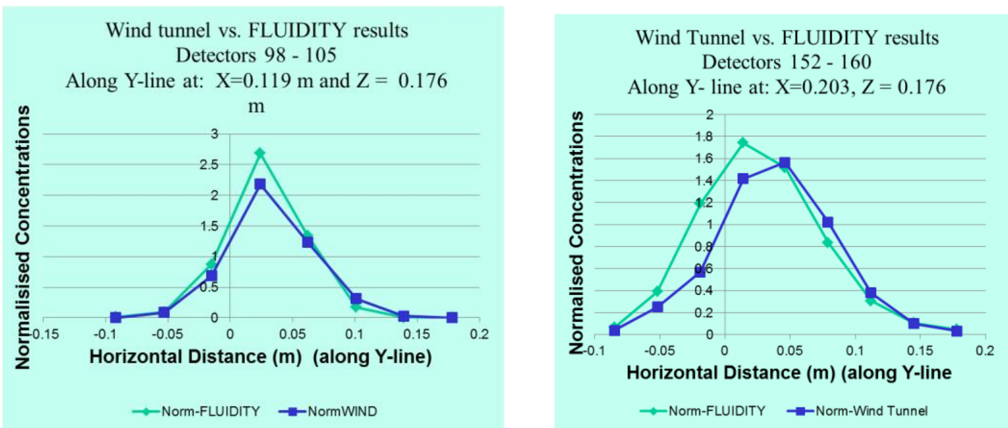
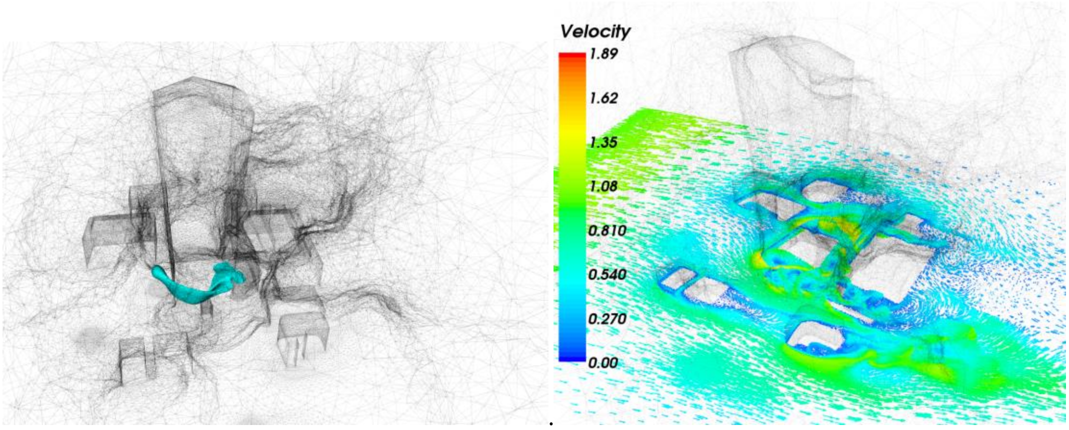


Figure 4 Comparison of simulated normalised FLUIDITY tracer concentrations with wind tunnel measurements from the Enflo wind tunnel.

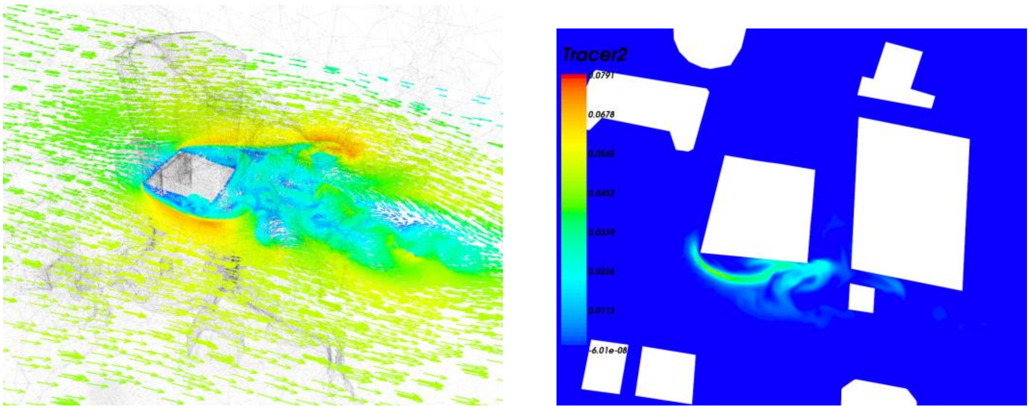
EFFECT OF BUILDING DESIGNS ON TURBULENT AIR FLOWS & DISPERSION

The rapidly changing landscape of London has led us to investigate the effect of such tall buildings on the air flow patterns and subsequent dispersal of pollutants. We have chosen to study the effect of the "Walkie-Talkie" building, due to its curved walls and curved roof, as well as its height. A preliminary set of Large Eddy Simulation results are shown in Figures 5 and 6, allowing identification of "dead" zones and demonstrating the effect of the building designs in the surrounding air flow turbulence and subsequent dispersion of pollutants.



(a) Tracer Iso-surface (b) Complex turbulent air flows at ground-level

Figure 5 Three-dimensional view of Adaptive mesh-refinement around the "Walkie-Talkie" building area, Central London together with: (a) a tracer isosurface and (b) the complex flow field near ground level.



(a) Half-way of the Walkie-Talkie Building (b) Tracer 2 around the" Walkie-Talkie" building

Figure 6 Complex, turbulent flows and dispersion around the "Walkie-Talkie" building area at two different heights.

CONCLUSIONS

Complex turbulent flows have been accurately captured using an LES approach with a novel anisotropic eddy viscosity model. The LES simulations were compared with wind tunnel data for a particular building configuration, with good correlations between experiments and simulations. The effect of tall buildings and their design on the distribution of "dead" zones has also been investigated, highlighting the importance of detailed modelling in the process of reducing and controlling air pollution within the urban environment.

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