Modelling flow and pollutant dispersion in urban areas

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ABSTRACT

This work presents some of the results from wind tunnel experiments in urban areas performed in the EnFlo laboratory, University of Surrey. The studies were carried out for two separate projects.

The first study was part of the multi-disciplinary DAPPLE project. The experimental set up allowed the measurement of flow and dispersion in a small-scale model of the DAPPLE site in central London, as well as the estimation of mean and turbulent fluxes in the urban canopy. Streamlines, vorticity, mean and turbulent velocity plots were produced. The complex 3-dimensional velocity field across the site was strongly affected by the geometry of the site and its orientation with respect to the wind direction studied. Mass balance calculations revealed the significant effect of the flow close to the ground in the estimation of the pollutant dispersion.

The second project (HRModUrb) is aimed at studying urban atmospheric flow and pollutant dispersion at the neighbourhood scale. The study methodology involves the use of wind tunnel experiments as well as numerical simulations (CFD) in order to enhance understanding of the dispersion phenomena at this particular scale. The preliminary results of the first phase of the project are reported. They include experimental measurements within different models of urban areas. The first results highlight the influence of the building height variability on the spatial averaged profiles. Further results will be available before the conference.

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1. INTRODUCTION

Much of the global population currently live and work in urban areas, and this urbanisation is expected to increase. This trend has recently inspired many urban-centred fluid mechanics studies, either in isolation or in combination with other disciplines such as chemistry, epidemiology, and pedestrian and vehicular mobility.

This work presents the results from two different experimental studies, carried out in small scale models of urban areas.

The first part of the research presented here is about several wind tunnel experiments in urban areas performed in the EnFlo laboratory, University of Surrey. The studies were carried out as part of a multidisciplinary project, Dispersion of Air Pollution and its Penetration into the Local Environment (DAPPLE – Arnold et al., 2004), whose aim is to enhance understanding of pollutant dispersion processes in realistic urban environments. One of the novel aspects of DAPPLE, if compared to other similar studies, is its multidisciplinary approach to the problem: field measurements on meteorology, background pollution levels, traffic flow, personal exposure and inert tracer releases were supported by both wind tunnel and numerical studies. Furthermore, it focussed on a real urban intersection, characterised by buildings of different shape and height, not infinite and uninterrupted canyons of different width and length.

The second part of the work was carried out in the framework of the HRModUrb project, funded by the EC under the FP7 People programme (Marie Curie Actions). This project is aimed at studying urban atmospheric flow and pollutant dispersion at the neighbourhood scale. Current state-of-the-art dispersion models have been developed for coarser scales and lower resolutions, and they are not capable of correctly reproducing the spatial and temporal distribution of air pollution within the urban environments where most people live (see e.g. urban street canyons). The neighbourhood scale allows for both a detailed reproduction of the phenomenon and the development of parameterised operational models. The study methodology involves the use of wind tunnel experiments as well as numerical simulations (CFD) in order to enhance understanding of the dispersion phenomena at this particular scale.

Neighbourhood scale models must take into account dispersion phenomena that occur in the urban canopy. However they cannot resolve the small-scale flow around each individual building, thus some kind of parameterisation must be attempted. The current approaches rely on empirical parameterisations derived from analytical studies and/or few experimental data gathered mostly on very simplified geometries (e.g. single 2D street canyon), or full-scale measurements (usually very case specific).

Most of the flow canopy models make use of spatially averaged velocity profiles and, in some cases, even a single spatially averaged canopy velocity ($U_c$, see Bentham & Britter, 2003). These variables depend strongly on the local geometry. In order to describe the latter, parameters such as the mean building height ($H_b$), the plan area index ($\lambda_p$) and the frontal area index ($\lambda_f$) are generally used. However, several other geometric characteristics may have a strong influence, for example the building height variability.

The distribution of pollutants in the canopy obviously strongly depends on the velocity field within the streets. Given the particular nature of the flow in dense urban areas, where recirculating flows are often observed in street canyons and in the wake of the buildings, pollutants tend to accumulate in the canopy, and thus the exchange mechanisms between the canopy and the flow above and between street and street become very important (Catton et al., 2003; Soulhac, 2000). These fluxes are rarely measured in urban experiments (full scale or laboratory scale), especially the turbulent fluxes that are likely to be dominant for the vertical exchange processes.

2. WIND TUNNEL MODELLING: DAPPLE

A simple physical model (scale 1:200) of an urban area centred on the intersection between
Marylebone Road and Gloucester Place in central London was reproduced in the EnFlo wind tunnel. A comprehensive database of experimental measurements of the flow within the intersection was built, involving both qualitative and quantitative techniques. The concentration of a tracer gas across the area was also measured. LDA (Laser Doppler Anemometry) and FFID (“Fast” Flame Ionisation Detector) devices were then coupled in order to produce simultaneous measurements of velocity and concentration, allowing the estimation of instantaneous and turbulent pollutant fluxes, thus giving an important insight into the understanding of turbulent diffusion.

![Figure 1: The 1:200 basic block model of the DAPPLE site in the EnFlo wind tunnel (left; WCC, Westminster City Council; MH, Marathon House); and, 3-D rendering of the central part of the DAPPLE site model (right).](image)

3. RESULTS OF THE DAPPLE EXPERIMENTS

The flow visualisation (FV) experiments highlighted the complexity of the case-study. Complex 3-dimensional flows were observed, particularly in the upwind zone of the studied intersection, where three different fluxes (from Gloucester Place, from Marylebone Road, and from the above-canopy flow) interacted. This behaviour cannot be correctly reproduced by current state-of-the-art street canyon and urban dispersion models, which have mostly a 2-dimensional approach. The analysis of the video records from the FV experiments pointed out another important characteristic: intermittently (and apparently randomly) the observed average flow is strongly perturbed for a limited period of time, with the formation of intermittent vortices and changes in the flow paths. The relevant time scale is not obvious and there are many potential candidates from the canopy and the external flow. The result though could be a significant redistribution of mass transfer and hence pollutant concentrations in the intersection – in other words, a major contribution to the variability in pollutant distribution. The phenomenon deserves further investigation in order to understand the controlling features and then develop more reliable dispersion models for this and similar complex situations.

The LDA measurements confirmed the qualitative analysis performed with the FV technique, although no information about the intermittent behaviour previously observed has been obtained. Measurements were performed over the whole intersection area, with a high resolution grid, for the three components of velocity and turbulence. This allowed the production of a very detailed map of the flow field and the estimation of flow stream traces. Comparing the resulting maps with the classical, ideal street canyon intersection behaviour one important fact can be noticed: in this complex real situation some details of the upwind flow, such as the presence of two tall towers upon the buildings, play an important role on the definition of the flow field within the intersection, particularly at roof level. This effect is likely to strongly influence the mass exchange mechanism...
between the canopy flow and the air aloft, and therefore the pollutants distribution. The particularly asymmetric geometry of the studied area enhances the interaction of the canopy with the above flow motion, as opposed to the classic ideal street canyon flow, where this interaction is weak and models usually consider the two flows separately.

![Figure 2: Flow visualization (snapshot); source at Gloucester Place (centre), horizontal light sheet at 20 mm in Marylebone Road showing vortex at the south-east corner of the intersection.](image)

The tracer concentration measurements were located where flow measurements were also available. This allowed for a mass flux balance to be calculated at the intersection. The proposed methodology was based on the calculation of the average mass fluxes through the four vertical sections constituting the interface between the street canyons and the intersection. The mean flux through the top horizontal section was also estimated. One important result from this is the level of mean flux observed between the southern and the northern parts of Gloucester Place. Given the wind direction and the intersection geometry, one might have expected all the tracer emitted in that street to be entrained into the wider Marylebone Road. On the contrary, flow instabilities and three-dimensional effects within the intersection resulted in about 13% of the incoming mean flux from Gloucester Place to continue along that street, north of the intersection. This feature is not necessarily observed in more regular street canyon intersections (Soulhac et al., 2009), and should be taken into account by street intersection dispersion models. Many regulatory models neglect any
interactions of the type found here and simply add the contributions from the two streets forming the intersection, thus neglecting the 85% of the flux from Gloucester Place that transfers into Marylebone Road (east) and the 50% of the flux from Marylebone Road into Gloucester Place (north).

Figure 4: Stream traces for the flow field at the highest horizontal levels (the starting points for the stream traces, forward and backward, are along a diagonal line across the intersection directed from NW to SE at \( z = 150 \) mm; where the traces are not visible they are outside of the measurement domain \( 300 \text{ mm} < x, y < 300 \text{ mm}, 25 \text{ mm} < z < 150 \text{ mm} \)).

Figure 5: Mass exchange balance expressed in terms of the total outgoing fluxes.

An experimental technique to measure mean and turbulent mass fluxes within several street intersections within the 1:200 model in the wind tunnel was developed. The experiments were conducted in order to calculate mass flux balances for the assessment of pollutant exchange between the streets of an intersection. Despite the fact that only one wind direction was used, results are quite heterogeneous, highlighting the strong influence of the intersection (and surrounding area) geometry. Generally, horizontal turbulent mass fluxes were found negligible with respect to the average mass flux driven by the advection mechanism. Measurements of vertical turbulent fluxes highlighted the increase of turbulent exchange at roof level, confirming the importance of this process in the exchange between canopy and external flow process.
4. WIND TUNNEL MODELLING: HRMODURB

The objective of the first series of experiments in the HRModUrb project was to broadly address the issues described in the introduction. In order to investigate the influence of the local geometry on the studied phenomena, several models were employed. They have the same “lambda parameters” ($\lambda_p$ and $\lambda_f$) but different arrangements. Because of the extensive work carried out on it previously and the experience gained, the DAPPLE model (see above) will also be used during the next series of experiments, in order to compare the results. Simpler urban models were purposely built for this project. They were arranged by using several regular building blocks. The models are simple building arrays, but somewhat more realistic than the regular and staggered arrays of cubes generally used for physical modelling. In order to study the influence of height variability on flow and dispersion, both constant height and variable height models were employed.

During the first series of experiments the same approach flow as in the DAPPLE wind tunnel tests were used. Only neutral conditions were simulated and most of the runs were carried out using a 2.5 m/s reference wind speed. Several wind directions were applied by means of the rotating turntable in the wind tunnel.

In order to obtain the spatially averaged velocity profiles, the horizontal flow field was measured with a high resolution grid mainly around the central intersection up to a height of $\sim 3 H_b$. Previous studies showed that at least 5-minutes averages would be necessary to obtain stationary velocity measurements, especially within the more complex models (Carpentieri et al., 2009). Given the time constraints, however, the runs were conducted by using 1 to 2.5 minutes averages. An estimation of the uncertainties arising from this choice was made.

4.1 The models

The starting point for the urban area models to be used during the experiments is the 1:200 scale DAPPLE model. A huge amount of data has been gathered in wind tunnel experiments, field tests and numerical simulations on the DAPPLE site, and can be used as comparison data for the simpler models. Other tests will be carried out on the DAPPLE model during the HRModUrb project in further experiments. The simpler models were designed on the basis of the morphological characteristics of that model (see figure 6).

![Figure 6: 3D representation of the DAPPLE model (1:200).](image)

The simplest models are regular arrays of buildings. They were arranged in a slightly more realistic way than usual, with two main intersecting streets (approximately matching those of the DAPPLE model: Marylebone Road and Gloucester Place) and several smaller streets. The
dimensions (width) of the main streets are, respectively: 220 mm and 110 mm. The building blocks occupy an area of 230 x 350 mm². In order to match the DAPPLE site \( \lambda_p = 0.54 \), an array of 6 x 8 buildings was built, with the secondary streets width equal to 99 mm (see figure 7).

As far as the vertical dimensions are concerned, two different models were employed in order to investigate the influence of the building height variability on the flow and dispersion phenomena. The simplest model (named ‘SimpleC’) has a constant building height \( H_b = 102 \) mm, which is the mean building height of the central part of the DAPPLE model. Another model (‘SimpleV’) with variable building heights was designed. Five different building heights have been used; the height of the DAPPLE model buildings were divided in classes of different height ranges (55-75 mm, 75-95 mm, 95-115 mm, 115-155 mm, 155-170 mm); the number of the buildings in a single class had to match that of the DAPPLE model. A building height of 102 mm was chosen for the 95-115 mm class for practical purposes. The other building heights were adjusted in order to have the same mean height (102 mm), \( \lambda_f (0.24 \) for wind direction parallel to the X axis, and 0.16 for wind direction parallel to the Y axis) and height variability (\( \sigma_H = 32 \) mm) as the DAPPLE model. The SimpleV model is then constituted of the following buildings: 8 x \( H_1 \) (65 mm), 20 x \( H_2 \) (85 mm), 8 x \( H_3 \) (102 mm), 4 x \( H_4 \) (135 mm), and 8 x \( H_5 \) (162 mm).

Other arrangements will likely to be studied in future experiments. In particular two other models (‘IrregC’ and ‘IrregV’, respectively with constant and variable building heights) are anticipated. These will be made using the same building blocks of the SimpleC and SimpleV models, but the arrangement will be less regular than in those models. In order to investigate the influence of the morphological parameters slightly different models will be studied by means of numerical simulations and the opportunity of conducting new wind tunnel tests will be assessed at a later stage.

4.2 Methodologies

The technique used for the evaluation of the mean and turbulent mass exchange between the canopy and the flow above is the same described for the DAPPLE experiments, involving the coupled use of laser Doppler anemometry (LDA) and a fast response flame ionisation detector (FFID) for measuring the concentration fluctuations. The averaged velocity profiles were measured by means of LDA, but the use of the particle image velocimetry (PIV) technique will be assessed.

5. RESULTS OF THE HRMODURB EXPERIMENTS AND FUTURE DEVELOPMENTS

Six experimental cases were tested for the LDA measurements. They were tagged as T04, T05 and T06 for the experiments in the SimpleC model (respectively with a model rotation of 0°, -90° and -45°), and T13, T14 and T15 for the SimpleV model (same wind directions). The measurement points for the vertical profiles are shown in figure 8.
It is not easy to make general comments about the measured vertical profiles of velocity and turbulence, given the differences in the local geometry for each profile. One obvious difference can be found, for example, between profiles in street canyons perpendicular to the approach flow (Y street in T04 and T13, and X street in T05 and T14) and profiles in streets parallel to the approach flow (X street and the intersection in T04/T13, Y street and the intersection in T05/T14). Turbulence peaks can be found almost everywhere at roof level. In the SimpleV model, however, other peaks
appear to be evident, since several buildings of different height are present upwind of the intersection. The differences in the geometry and the arrangement of the buildings for the tests carried out, is reflected in the differences in the averaged profiles calculated and shown in figure 9. Marked differences can be found both in the in-canopy and above-canopy parts of the profiles. Further analysis is needed to choose the affecting parameters, derive sensible parameterisations and to check the current approach in deriving the averaged profiles.

Further analysis and comparisons are being attempted using the above LDA data. The aim is to derive new parameterisations and check the current approaches in neighbourhood scale modelling. Coupled FFID and LDA measurement are also being analysed and results on the derivation of mean and turbulent fluxes will be presented at the conference poster. Other wind tunnel experiments will be carried out in the next months, while further insight will be given by numerical CFD simulations with the open source code OpenFOAM. The HRModUrb project is due to end in May, 2010.

REFERENCES


