5.12 AIRFLOWS IN THE VINCINITY OF AN INTERSECTION

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INTRODUCTION

Intersections and street canyons form the urban traffic network. It has been observed that pollution concentrations peak near signalised traffic intersections where queuing occurs, and level off towards the mid-links where vehicles move steadily. This distribution pattern of pollutant concentration is similar to that which results from an individual source, and therefore implies that an intersection may be the source that dominates road-users' exposure to traffic pollution. This is not surprising; vehicles produce more pollutants during deceleration and acceleration when queuing near intersections than when cruising steadily.

Wind velocity and pollutant concentration can change rapidly over time and space within a certain microenvironment, even with a given unchanged boundary condition, due to the transient natures of turbulent flow. The results of preliminary tracer dispersion experiments of the DAPPLE project (www.dapple.org.uk; Arnold et al., 2003) using a 1:200 scale model of the Marylebone Road – Gloucester Place site in the EnFlo wind tunnel showed individual concentration realisations differed greatly from the ensemble mean, and the peaks in the realisation, spaced in about 2 to 3 minutes (full time scale), were several times greater than ensemble average (Robins and Cheng, 2003). Similar phenomena were observed in one of the street canyons of an isolated intersection in the EnFlo wind tunnel (Bentham et al., 2003).

Kaur et al. (2003) measured personal exposure of people passing through the DAPPLE domain by sampling pollutant concentrations in their breathing zone as they moved along pre-determined routes by different modes of transport. Wind speed, mode of transport, and route were found to be determinants of exposure, in agreement with the findings of Adams et al. (2001), but a large amount of variability in exposure remains unexplained. It is likely that much of the variability is caused by in homogeneity of the emissions and variation in distances between polluting vehicles and exposed people, and a prototype DAPPLE Exposure Model (DEMo)(Colvile et al., 2003) illustrates how correlation between the location of people and the location of emissions as a signal controlled junction is important. It is unknown however, to what extent the unsteadiness of the dispersion patterns contributes to variability in exposure, and quantifying all the sources of variability is one of the main objectives of the DAPPLE project.

This paper is the first to present the application of large eddy simulation (LES) to the prediction of transient turbulent flow patterns under a given wind direction in the vicinity of the intersection in an attempt to understand how turbulent transient feature contributes to personal exposure near the intersection. The code used is called FLUIDITY (Pain et al., 2001) and uses a dynamically changing mesh to simulate the important flow features. We focus here on the model predictions of flow velocity in the vicinity of the intersection, which is important in determining which emissions are responsible for the highest exposure levels.

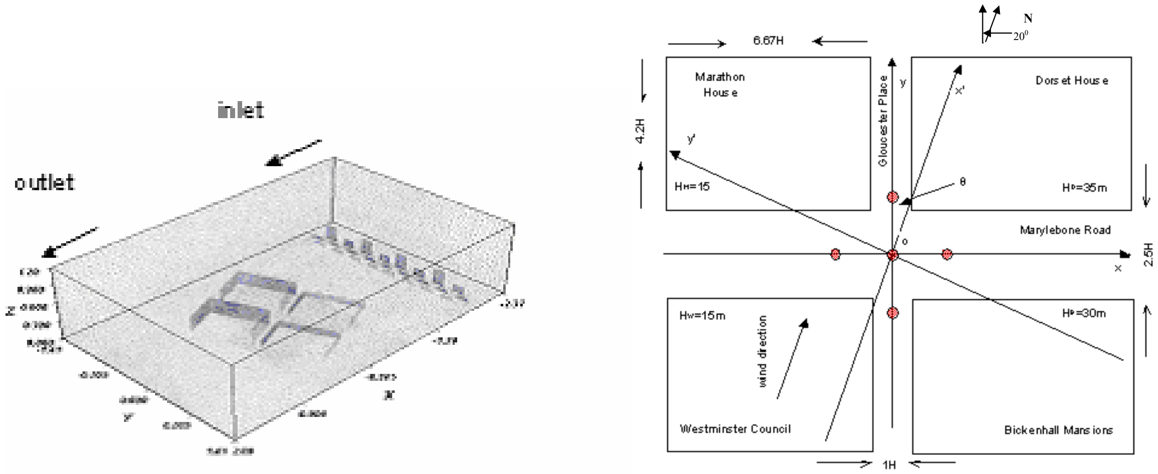
METHODOLOGY

Numerical model

Among the CFD models, LES is considered to be a computationally affordable way to predict turbulent transient behaviour to the extent that it resolves large-scale turbulent motions and models small homogeneous ones. FLUIDITY, developed at Imperial College London, is a general CFD code that adopts adaptive mesh method. Besides the standard Smagorinsky model, it contains three Smagorinsky type LES model options, one isotropic model (SFS-I) and two anisotropic ones (SFS-a1 and SFS-a2). Bentham et al. (2003) tested SFS-a2 to be the best in the simulations of flow past a bluff body. This paper therefore uses this model to simulate airflows near the intersection.

The intersection simulation

The original dimensions of Marylebone Road – Gloucester Place intersection are described by Scaperdas and Colvile(1999). The computational domain, illustrated in Figure 1 (b), was a box whose dimensions were $37.5H\times25H\times 10H$ in the streamwise, span wise and normal directions respectively, where H is the height (15 m full-scale) of Westminster Council House. The scaled dimensions for both Westminster Council and Marathon House are H high$\times$6.67H long$\times$4.44H wide, for Bichenhall Mansion are 2H high$\times$6.67H long$\times$4.44H wide, and for Dorset House are 2.33H high$\times$6.67H long$\times$4.44H wide. The model was rotated anticlockwise 22.5^{o} looking from the top of the domain (Figure 1(a)(b)). The Cartesian coordinate axes x', y', z' applied in LES computation were chosen to be coincident with the sides of the rectangular domain. Incident flow of constant velocity U was made turbulent by three equally spaced rows of staggered spires similar to those used in a wind tunnel. The element size for the region in the vicinity of the intersection was forced to lie approximately between H/20 and H/10. The maximum number of nodes was 350,000, with a time-step of 0.089H/U. Results are presented with time scaled to a full-scale for comparison with a day of field measurements when the roof-top wind speed was 3 m s^{-1}.



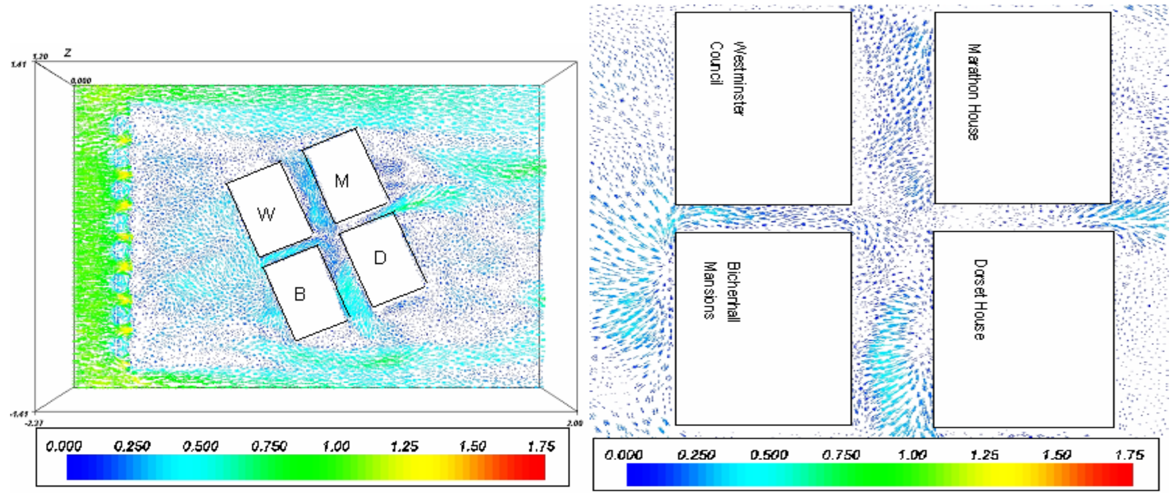
(a) *(b)*

Figure 1. (a) Computational domain, mesh at 510s full-scale time. (b) Plan of model arrangements and coordinate axes. The red filled circles are detectors to record time series of variables. x', y'are axis used in LES computation, whereas x and y system are adopted to discuss the results. The streets are named according to the initial letters of the buildings alongside, e.g. W-M runs between Westminster Council House and Marathon House.

RESULTS AND DISCUSSION

Flow patterns around the intersection

Figure 2(a) shows that turbulent inflow was produced by the spires and roughness elements



(a) *(b)*

Figure 2. (a) Wind velocity distribution on the plane z=H/2, t = 510s; (b) z=H/7.5, t = 510s

prior to entering street canyons. The area of distinct flow pattern can be easily recognized in the vicinity of the intersection. Beyond this area some distance into the constituent streets the airflows behaved virtually the same way as they would in a stand-alone street canyons. Figure 2(b) shows wind vectors on planar section at the height where $z=H/7.5$, which corresponds to 2 m above the ground at full scale and supposed to be the height of a road-user's breathing zone. In most parts of the W-M and B-D streets some distance away from entrances or exits to the intersection, winds have significant components towards the leeward sidewall, indicating the existence of the street canyon vortex. In the M-D and W-B streets the winds were generally along the streets. The winds within the intersection were very complex.

TIME SERIES OF WIND VELOCITY WITHIN THE INTERSECTION

Table 1 shows the positions of two detectors located along the vertical line starting the centre of the intersection on the ground up to the top of the computational domain, one at the ground level and the other at $z=0.44H$. Turbulent flows were regarded as being fully developed after $t=240$s, because after that point the velocity high above the building ($z=6.22H$) became steady (graph not presented in this paper).

At ground level, $z = H/10$, as can be seen in Figure 3(a), the wind speed was very low, the maximum approximating $0.08U$, and w was almost zero. The wind was between 20 to 110° (measured anticlockwise from the x-axis), spanning about 90°, and thus indicating highly variable wind direction. The wind speed fluctuated between $0.02U$ and $0.08U$, with a time

Table 1. Detectors chosen within the intersection

Detector location			Description
x/H	y/H	z/H	
0	0	0.1	Centre of the intersection, detectors at various heights.
0	0	0.44	
-1.69	0	0.1	In W-M street, ground level.
1.69	0	0.1	In B-D street, ground level.
0	1.69	0.1	In M-D street, ground level.
0	-1.69	0.1	In W-B street, ground level.

Note: detectors are those points specified to record time series of variable values.

scale of about 120s, which was consistent with the fluctuation of wind direction. At z=0.44H, the wind speed was higher than that on the ground level, the maximum being about 0.18U. The wind direction was between +0 and +100˚.

TIME SERIES OF WIND VELOCITY AT THE EXIT/ENTRANCE OF AIRFLOWS OF THE CONSTITUENT STREETS

Table 1 also presents another four detectors distributed at ground level at the exits of the upstream street and entrances to the downstream streets, in order to investigate the relationship between these positions with those at the centre. The detectors are shown in Figure 1(b).

At the exit of W-M street at ground level where $z = H/10$ as shown in Figure 3(c), the wind direction was between +10 and –40˚, attributable to the combined effects of street canyon vortex and the oblique roof wind. The wind speed was very low, the maximum approximating 0.1U, and w was almost zero. The wind speed fluctuated approximately about every 120s. At the entrance to B-D street, at ground level, $z = H/10$, as can be seen in Figure 3(d), the wind direction was between –10 and –80˚, with wind speed fluctuating between 0-0.1U. At the exit of W-B street (see Figure 3(e)), the wind direction varied between 45 and 70˚, the smallest fluctuation compared with other positions chosen and the wind speed was between 0.05 and 0.15U. At the entrance to the M-D street (Figure 3(f)), the wind direction showed intermittent change from positive direction to negative direction, the wind speed being between 0 and 0.1U. Similar fluctuations were observed in the field, where they were accompanied by marked changes in vehicle exhaust pollutant concentration and on-street receptor locations. This phenomenon is therefore interesting and needs further investigation.

CONCLUSION

The numerical method of large eddy simulation to study the wind velocity field in the vicinity of intersection was shown to be very promising, despite the short time simulation obtained. The capability of a dynamical self-adaptive grid resolution incorporated in FLUIDITY guarantees the most accurate solution for the least computational effort. It also frees the user from the burden of choosing the most appropriate computational grid.

The flow visualisation of this simulation shows that the airflows near the intersection have distinct patterns adjoining to the purely street-canyon flow patterns which have been extensively studied. The wind direction within the intersection is seen to be more variable than those which occur some distance into the streets, suggesting the difficulty to seek a relation between the wind on the ground level and that above the roof at least over a time scale of as short as two minutes, due to highly variable wind direction on the ground level with constant upwind conditions.

A time scale of about two minutes has been detected for velocity fluctuation. This is comparable with the time scale of changes in emissions from traffic at a signal-controlled road junction, and with the time road users spend in the vicinity of the intersection. Further study will be carried out using LES to investigate how time-dependent traffic emissions near the intersection coupled with wind velocity fluctuations contribute to road-user exposure.

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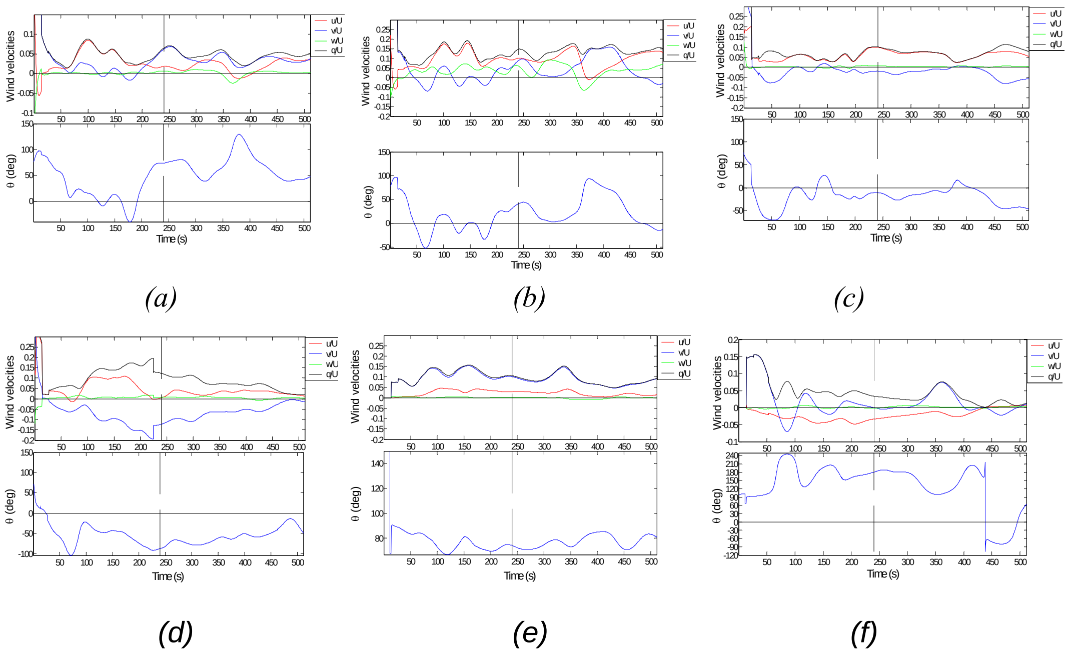

Figure 3. (a) Time series for wind velocities, x=y=0, z=0.1H; (b) x=y=0, z=0.44H (c) x=0, y=1.69H, z=0.1H; (d) x=0; y=-1.69H, z=0.1H; (e) x=-1.69H, y=0, z=0.1H; (f) x=1.69H, y=0, z=0.1H

REFENRENCES

Adams, H.S., Nieuwenhuijsen, M.J. and Colvile, R.N., 2001. Determinants of fine particle (PM2.5) personal exposure levels in transport microenvironments, London, UK. Atmospheric Environment, 35(27): 4557-4566.

Robins, A. and H. Cheng (2003). "Initial dispersion experiments in the EnFlo wind tunnel." Note DAPPLE - EnFlo 01.

Bentham, T., Pain, C. and Colvile, R., 2003. Large-eddy simulation in complex geometries using anisotropic mesh adaptivity. Submitted to Atmospheric Environment.

Colvile, R, Wang H., Bentham J. T., et al., 2003. Modelling the relationship between urban form and variability in exposure to vehicle emissions. 13th Annual conference, International Society of Exposure Analysis, Abstract Book: 280.

Kaur S., Nieuwenhuijsen, M.J. and Colvile, R.N., 2003. Exposure of road users to air pollution at a street can yon. 13th Annual conference, International Society of Exposure Analysis, Abstract Book: 281.

Pain, C.C., Umpleby, A.P., de Oliveira, C.R.E. and Goddard, A.J.H., 2001. Tetrahedral mesh optimisation and adaptivity for steady-state and transient finite element calculations. Computer Methods in Applied Mechanics and Engineering, 190(29-30): 3771-3796.

Scaperdas, A. and Colvile, R.N., 1999. Assessing the representativeness of monitoring data from an urban intersection site in central London, UK. Atmospheric Environment, 33(4): 661-674.