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Short communication

Wind tunnel measurements of pollutant turbulent fluxes in urban intersections

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ABSTRACT

Wind tunnel experiments have been carried out at the EnFlo laboratory to measure mean and turbulent tracer fluxes in geometries of real street canyon intersections. The work was part of the major DAPPLE project, focussing on the area surrounding the intersection between Marylebone Road and Gloucester Place in Central London, UK. Understanding flow and dispersion in urban streets is a very important issue for air quality management and planning, and turbulent mass exchange processes are important phenomena that are very often neglected in urban modelling studies. The adopted methodology involved the combined use of laser Doppler anemometry and tracer concentration measurements. This methodology was applied to quantify the mean and turbulent flow and dispersion fields within several street canyon intersections. Vertical profiles of turbulent tracer flux were also measured. The technique, despite a number of limitations, proved reliable and allowed tracer balance calculations to be undertaken in the selected street canyon intersections. The experience gained in this work will enable much more precise studies in the future as issues affecting the accuracy of the experimental technique have been identified and resolved.

1. Introduction

High pollution levels are often associated with street canyons, that is in urban streets flanked by buildings on both sides. Street canyons are not infinitely long or isolated entities in cities, but they are often segmented and connected to other canyons at urban intersections. There have been only a few dispersion studies focussing on urban canyon intersections, where flow patterns and dispersion behaviour can be markedly different to those in idealised, isolated street canyons (Hoydysh and Dabberdt, 1994; Carpentieri et al., 2009; Carpentieri and Robins, 2010).

Urban canyon intersections constitute pollutant exchange areas between several streets, and between the street canopy and the flow above. Understanding these exchange processes is therefore important in order to develop local and neighbourhood scale dispersion models for urban areas. This is not easy as the geometry of real intersections leads to complex three-dimensional flows and associated dispersion conditions. In addition to mean flow processes, turbulent fluxes may play a significant role in exchanging pollutants between streets and with the flow above the canopy (Soulhac, 2000; Caton et al., 2003). Despite this, most street canyon and street intersection dispersion modelling studies focus only on mean fluxes, due to the difficulties arising in measuring concentration and velocity fluctuations at the same time and location.

Conventional measurement techniques have been applied in the past to measure turbulent mass fluxes (see, e.g., Fackrell and Robins, 1982; Zhu et al., 1988; Lemoine et al., 1997), but never used to measure fluxes in street canyons. Dezső-Weidinger et al. (2003) developed an alternative measuring technique involving Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) and applied it to a two-dimensional street canyon with a regular shape in a wind tunnel. They were particularly interested in assessing the proportionality between turbulent mass fluxes and concentration gradients, finding proportionality in the 2D shear region, but not within the canyon. However, they did not try to calculate integral mass fluxes through the interface between the canopy and the region above. Caton et al. (2003) applied a similar PTV technique in a water flume in order to validate their model for pollutant mass exchange between the canopy and the region above. Only mean mass fluxes were estimated, though, while no attempts were made to measure turbulent fluxes.

An interesting technique for measuring scalar fluxes in wind tunnel models of street canyons and, more generally, urban areas was developed by Barlow and Belcher (2002) using naphthalene sublimation (see also Barlow et al., 2004; Pascheke et al., 2008). This experimental technique can be used to estimate space averaged total mass fluxes, thus including turbulent fluxes, but cannot

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distinguish between the mean and turbulent components. A similar technique was used by Narita (2007), with water evaporation instead of naphthalene.

The research presented in this paper addresses the issue of measuring turbulent fluxes in urban areas. An experimental technique for directly measuring both mean and turbulent tracer fluxes in small-scale models of urban areas has been developed. It involves the combined use of a two-component laser Doppler anemometer (LDA) and a fast response flame ionisation detector (FFID). The two instruments had already been used separately in order to estimate the mean pollutant fluxes in and around a street canyon intersection (Carpentieri et al., 2009; Carpentieri and Robins, 2010) – they were used together in the present work in order to be able to separately measure the turbulent tracer fluxes as well. Once developed, the technique was then applied to a small-scale model of a real urban area, in central London, UK.

The need to develop a technique to measure turbulent mass fluxes arose from the outcomes of previous experimental studies (Carpentieri et al., 2009; Carpentieri and Robins, 2010). The work was part of part of DAPPLE (Dispersion of Air Pollution and its Penetration into the Local Environment), a 4-year UK Engineering and Physical Sciences Research Council (EPSRC) funded project within the Engineering for Health, Infrastructure and Environment Programme (Arnold et al., 2004) that continued under a 3-year follow-up project (DAPPLE-HO) funded by the UK Home Office (Wood et al., 2009).

The DAPPLE site (e.g. see also Carpentieri et al., 2009) is located around the intersection between Marylebone Road and Gloucester Place in Central London, UK. The roads intersect perpendicularly and Marylebone Road runs approximately from west-south-west to east-north-east. The average building height is approximately 22 m. As it is a real site, the heights and sizes of the buildings and streets are all different and this strongly influences the pollutant dispersion mechanism within the intersection (Carpentieri et al., 2009; Carpentieri and Robins, 2010).

2. Experimental set-up and strategy

The experiments were carried out in the boundary layer wind tunnel of the Environmental Flow Research Centre (EnFlo), at the University of Surrey, UK. This is an open circuit wind tunnel with a 20 m long, 3.5 m wide and 1.5 m high working section. The wind speed can be in the range 0.3–3.5 m s^{-1}, and the facility is capable of simulating both stable and unstable atmospheric conditions, although this feature was not used in this study. Reference flow conditions are measured by two ultrasonic anemometers, one held at a fixed location and the other positioned as required, and two propeller anemometers mounted on either side of the traverse carriage; the motor shaft speed was also measured. Temperature conditions are monitored by thermocouple rakes in the flow and individual thermocouples in each tunnel wall panel. The wind tunnel and its associated instrumentation are fully automated and controlled using virtual instrument software created by EnFlo research staff using LabVIEW.

The 1:200 model installed in the wind tunnel is the simplest version of the DAPPLE site model, where all buildings have been reduced to simple blocks with flat roofs (see Fig. 1-left). The boundary layer was generated using Irwin spires and surface roughness upwind of the model, obtaining a thickness of 1 m and a surface roughness $z_0 = 1.5$ mm (equivalent to 0.3 m at full scale). The reference wind speed (U_{ref}) was set to 2.5 m s^{-1}; U_{ref} was measured with the ultrasonic anemometer positioned just outside the simulated boundary layer. The model was oriented using a rotating turntable, and all the experiments were performed with a rotation of 51.35° in model coordinates (0° corresponds to a wind direction along the x axis, see Fig. 1-left; model rotation is positive clockwise, hence the selected wind direction is approximately from south-west); the wind direction being chosen to correspond to conditions of the first field tracer release experiment (Arnold et al., 2004).

The total tracer flux, Φ through a reference plane S is given by: $\Phi = \iint_S (U_n C + \langle u_n c \rangle) dS$, where U_n is the mean flow speed normal to the surface, C is the mean concentration (thus, $U_n C$ represents the mean tracer flux), and $\langle u_n c \rangle$ is the mean turbulent flux across the plane.

The experiments were performed using a Cambustion fast response (frequency > 350 Hz) Flame Ionisation Detector (FFID) for concentration measurements, in conjunction with a two-component Dantec Laser Doppler Anemometer (LDA), for the velocity measurements (see Fig. 1-right). This setup was capable of measuring the turbulent part of the flux along with the mean part at several locations within the urban model. The averaging time for the measurements was 1 min as in previous measurements on the same model (Carpentieri et al., 2009; Carpentieri and Robins, 2010).

Five street canyon intersections (labelled as 'A', 'B', 'C', 'D' and 'E') were selected for tracer flux balance analysis; these are shown in Fig. 2-left. The measurement sections (tagged with the initials of the street name and a number) and the various source positions (tagged as s1 to s7) used are also presented in this figure. Table 1

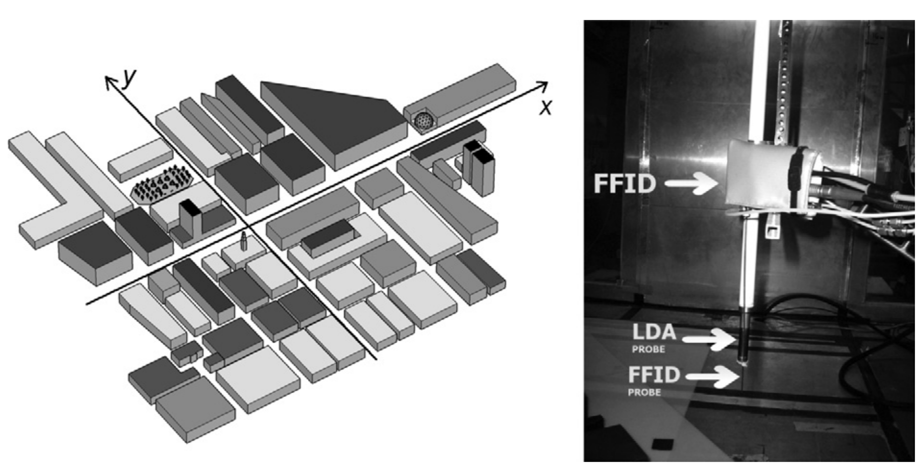

Fig. 1. Left: three-dimensional representation of the 1:200 DAPPLE model; the grey shades correspond to different building height ranges. Right: instrumentation used for the concentration and velocity measurements.