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Impact of roof height non-uniformity on pollutant transport between a street canyon and intersections☆

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ABSTRACT

This paper presents an extension of our previous wind-tunnel study (Nosek et al., 2016) in which we highlighted the need for investigation of the removal mechanisms of traffic pollution from all openings of a 3D street canyon. The extension represents the pollution flux (turbulent and advective) measurements at the lateral openings of three different 3D street canyons for the winds perpendicular and oblique to the along-canyon axis. The pollution was simulated by emitting a passive gas (ethane) from a homogeneous ground-level line source positioned along the centreline of the investigated street canyons. The street canyons were formed by courtyard-type buildings of two different regular urban-array models. The first model has a uniform building roof height, while the second model has a non-uniform roof height along each building's wall. The mean flow and concentration fields at the canyons' lateral openings confirm the findings of other studies that the buildings' roof-height variability at the intersections plays an important role in the dispersion of the traffic pollutants within the canyons. For the perpendicular wind, the non-uniform roof-height canyon appreciably removes or entrains the pollutant through its lateral openings, contrary to the uniform canyon, where the pollutant was removed primarily through the top. The analysis of the turbulent mass transport revealed that the coherent flow structures of the lateral momentum transport correlate with the ventilation processes at the lateral openings of all studied canyons. These flow structures coincide at the same areas and hence simultaneously transport the pollutant in opposite directions.

1. Introduction

The street network formed by buildings is an inherent part of a city. While the buildings have favourable effects on the well-being of city dwellers, e.g., offering shade from the sun during warm seasons, they have also unfavourable effects, e.g., preventing the ventilation of pollutants from traffic (Oke, 1988). The air quality then deteriorates not only in pedestrian zones but also inside the buildings that line the streets and intersections (Jin et al., 2016; Yang et al., 2016). Another health-related issue is the accidental or deliberate release of harmful substances within a local spot of a street network, and this is becoming more serious as most of the world's population lives in cities (Barlow, 2014).

Owing primarily to these health-related issues, extensive research on identifying and understanding the physical processes that drive and influence the near-field pollutant dispersion in urban environments has experienced substantial progress over the last three decades. While earlier studies relied on wind-tunnel (Hoydysh et al., 1974; Klein et al., 2007; Brixey et al., 2009; Carpentieri et al., 2012) or field (Allwine et al., 2002; Longley et al., 2004; Pol and Brown, 2008; Balogun et al., 2010) experiments, recent studies are focused more on numerical approaches, mostly using computational fluid dynamics (CFD) (Hamlyn and Britter, 2005; Gu et al., 2011; Michioka et al., 2014; Buccolieri et al., 2015) and, to some extent, semi-empirical models (Brown et al., 2015; Soulhac et al., 2016). Each of these approaches and their advantages and limitations have been recently reviewed by several studies (Lateb et al., 2016; Tominaga and Stathopoulos, 2016; Blocken et al., 2016). Lateb et al. (2016) clearly concluded that “the topic of micro-scale dispersion still requires further investigation to understand the effect of all parameters on wind

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flow and pollutant dispersion in urban areas” and that there “is a clear need for the development of computational methods for wind engineering applications utilising 3D numerical modelling of flow and dispersion fields around buildings.” However, all these reviews also concluded that the main limitation of CFD or semi-empirical models is that they still require validation against experimental tests. Due to the recent increase in CFD studies, it is essential that the performance of quality experiments go hand in hand.

Although field experiments have the important advantage, in comparison to physical and numerical modelling, that they are conducted under real atmospheric conditions, these conditions are uncontrollable, and hence a repeat of the experiment under identical conditions is impossible (Schatzmann and Leitl, 2011). In addition, the number of measurement points is limited owing to financial or technical constraints. While the first disadvantage can be solved by wind-tunnel tests (providing an appropriately modelled atmospheric boundary-layer flow approaching a reduced-scale model), the latter is recently solved only by the CFD models (Lateb et al., 2016) since they compute the flow and concentration fields over the entire computational domain.

While several wind-tunnel studies, focused on pollutant dispersion within 3D urban-like arrays formed by blocks of uniform (Davidson et al., 1996; Brown et al., 2001; Garbero et al., 2010; Castro et al., 2017) or variable (Hoydysh et al., 1974; Klein et al., 2007; Heist et al., 2009) height, gave insight into the pollutant dispersion within such street networks, they lack the full urban three-dimensionality (variability of the obstacle geometry in all directions) at the cost of the highest possible geometrical simplification. The study of Nosek et al. (2016) showed by means of even and uneven roof height along each courtyard building's wall of a regular urban array that the pollutant fluxes and pollutant removal capabilities through the street-canyon roof top are strongly affected by those roof-height arrangements. That study confirmed the observations from the CFD study of Gu et al. (2011) and highlighted that the roof-height non-uniformities along both street-canyon walls are able to improve or worsen the street-canyon air quality with regard to the source position and above-roof wind direction. Interestingly, Nosek et al. (2016) also concluded that the 'vertical' turbulent coherent structures (known as sweeps and ejections) are highly correlated with ventilation processes (introduced by that study as entraining of clean air and venting of polluted air), irrespective of the canyons' roof-height arrangements and wind direction.

Conclusions drawn from two field campaigns, Joint Urban in Oklahoma city, Oklahoma, US (Pol and Brown, 2008) and DAPPLE in London, UK (Balogun et al., 2010), indicate that both the direction of the above-roof winds and the buildings' roof-height non-uniformity at the intersections play an important role in developing complex flow structures at the lateral ends of the canyons. These structures were found to be a combination of individual flow structures, such as horizontally rotating “corner” vortices at the canyon ends and converging or diverging flows from/into the adjoining canyons and intersections. Because these structures drive the pollutant exchange processes between the street canyon and intersections principally in the horizontal direction (Klein et al., 2007; Carpentieri et al., 2012), there is a clear need for additional experimental studies that will give better insight into these processes in that direction with respect to buildings' roof-height non-uniformity at these intersections. This will help to better understand the near-field pollutant dispersion phenomena for real cases of urban environments and provide the lacking experimental data for validation of CFD models.

The present paper is, therefore, principally an extension of the study of Nosek et al. (2016), and the aims are the following: (i) investigate the horizontal pollutant exchange processes at the lateral openings of the same uniform and non-uniform canyons with respect to the wind direction; (iii) find the correlations between the 'lateral' coherent structures and ventilation processes, similar to those for vertical pollutant transport; and (iii) observe the effect of the roof-height non-uniformity on the street-canyon pollutant exchange processes with respect to the regularity of the urban-array layout. To accomplish these aims, we performed additional wind-tunnel runs where both the turbulent and advective pollution fluxes were measured at each canyon's lateral openings for two wind directions, perpendicular and oblique (i.e., 45°) to the along-canyon axis. The pollution was simulated by homogeneously emitted passive gas (ethane) from a ground-level line source. The line source was positioned along the centreline of the investigated street canyons, crossing the adjoining intersection, and hence represented the pollution from idealised homogenous traffic.

2. Methods

2.1. Experimental setup

The experiments were conducted under neutrally stratified conditions in the Environmental wind tunnel of the Institute of Thermomechanics of the Czech Academy of Sciences. This is an open low-speed wind tunnel with cross dimensions of 1.5 × 1.5 m, and the lengths of the development and test sections are 20.5 m and 2 m, respectively. The freestream velocity can be maintained within a range of 0.1–10 m s^{-1} by means of a frequency convertor of the fan with an accuracy of 0.05 m s^{-1}. Because the pollutant dispersion in urban areas is related to the atmospheric boundary layer developed above terrain of such considerable roughness, the corresponding approaching boundary layer, with a scale of 1:400, was initiated by turbulence generators (a set of three spires, 1.4 m in height) and subsequently developed by a staggered array of roughness elements (thin plates of 50 mm in width and height) along the remaining part of the development section in the wind tunnel. The characteristics of the boundary layer were measured at the wind-tunnel freestream velocity $U_0 = 6.2$ m s^{-1} (measured using a Prandtl tube at a fixed position, 1 m above the wind-tunnel bottom and 4 m upwind from the test section) by 2D Laser Doppler Anemometry (LDA) at four positions between the roughness elements at the end of the development section. The position and characteristics of the best-fitted vertical profile are described in detail in Nosek et al. (2016), together with the aerodynamic parameters (roughness length, $z_0 = 1.87$ m; displacement height, $d_0 = 3$ m; and friction velocity, $u_* = 0.43$ m s^{-1}, all at full scale) and characteristics of turbulence. The mean near-surface streamwise and vertical intensities of turbulence were $I_u = 35\%$ and $I_w = 25\%$, respectively, and in good accordance with VDI (2000) guidelines. We also computed the integral length scales of the streamwise velocity component, L_{ux}, from time series measured at 7 different heights across the boundary-layer depth. For the heights $z_{FS} < 50$ m (full scale), these integral length scales were within the theoretical values for very rough terrain and in good accordance with the filed measurements (Counihan, 1975).

To study the effect of urban array three-dimensionality and wind direction on pollutant transport from traffic while keeping the configuration as simple as possible, we designed two urban array models according to the typical pattern of the centres of Central European cities (Fig. 1). Both idealised models were formed by evenly spaced 8 × 4 courtyard-type buildings of constant length ($L_{CB} = 300$ mm) and width ($W_{CB} = 150$ mm). The difference between the modelled urban arrays consisted of the heights of the pitched roofs of the courtyard buildings. While the reference urban model (A1) had a constant roof height ($H = 62.5$ mm, i.e., 25 m at