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Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings

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HIGHLIGHTS

- Intake fraction (*iF*) and daily CO exposure (E_t) are used for exposure assessment.
- Effects of aspect ratios ($H/W = 1$–6), viaduct/noise barriers are studied by CFD.
- $iF = 10^2$–10^4 ppm as $H/W = 1$–4 (one vortex) but $iF = 10^5$–10^6 ppm as $H/W = 5$–6 (two vortexes).
- Viaducts produce less CO exposure if only a viaduct-level CO source is fixed.
- Noise barriers slightly reduce vehicular indoor CO exposure as $H/W = 3$–6.

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ABSTRACT

Vehicular pollutant exposure of residents and pedestrians in high-rise deep street canyons with viaducts and noise barriers requires special concerns because the ventilation capacity is weak and the literature reported inconsistent findings on flow patterns as aspect ratios (building height/street width, H/W) are larger than 2. By conducting computational fluid dynamics (CFD) simulations coupled with the intake fraction *iF* and the daily pollutant exposure E_t, this paper investigates the impact of street aspect ratios, viaducts and noise barriers on the flow and vehicular passive pollutant exposure in full-scale street canyons ($H/W = 1$–6, $W = 24$ m). *iF* represents the fraction of total emissions inhaled by a population (1 ppm $= 10^{-6}$), while E_t means the extent of human beings' contact with pollutants within one day. CFD methodologies of passive pollutant dispersion modeling are successfully validated by wind tunnel data in Meroney et al. (1996).

As a novelty, the two-main-vortex pattern start appearing in full-scale street canyons as H/W changes from 4 to 5, however previous studies using wind-tunnel-scale models ($H = 6$cm) reported two to five vortexes as $H/W = 2$–5. This finding is validated by both smoke visualization in scale-model outdoor field experiments ($H = 1.2$m, $W = 0.6$m) and CFD simulations of Reynolds number independence. Cases with two main vortexes ($H/W = 5$–6) experience much larger daily pollutant exposure (~10^3–10^4 mg/m^3/day) than those with single main vortex as $H/W = 1$–4 (~10^1–10^2 mg/m^3/day). Moreover leeward-side pollutant exposures are much larger than windward-side as $H/W = 1$–4 while oppositely as $H/W = 5$–6. Assuming a general population density, the total *iF* is 485–803 ppm as $H/W = 1$, 2020–12051 ppm as $H/W = 2$–4, and 51112–794026 ppm as $H/W = 5$–6. With a single elevated pollutant source, cases with viaducts experience significantly smaller pollutant exposures than cases without viaducts. Road barriers slightly increase pollutant exposure in near-road buildings with $H/W = 1$ while reduce a little as $H/W = 3$ and 5. Two-source cases can experience 2.60–5.52 times pollutant exposure as great as single-source cases.

1. Introduction

Motor vehicle emissions are becoming the major sources of urban air pollutants, including particulate matter, carbon monoxide, benzene, nitric oxide etc. (Chan and Yao, 2008). The growing number of vehicles

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in cities and densely packed tall buildings flanking narrow streets can produce poor urban air quality in so-called 'street canyon' (Fig. 1) or within the urban canopy layer (UCL). Moreover, people spend more than 90% of their time indoors on average. As outdoor air pollutants could penetrate indoors via doors/windows, building cracks etc. (Chen et al., 2012a), the aggravated street air pollution can produce adverse effects on population exposure for both pedestrians and residents in near-road buildings (Chen et al., 2012b, 2012c; Ji and Zhao, 2015), especially for sensitive groups like children and the elderly.

Urban architectural parameters, meteorological conditions and pollutant emissions related to traffic volumes are the main factors influencing vehicular street air pollution (Gallagher, 2016; Santiago et al., 2017). As reviewed by the literature (Vardoulakis et al., 2003; Li et al., 2006; Fernando et al., 2010; Di Sabatino et al., 2013; Blocken, 2015; Lateb et al., 2016; Meroney, 2016), numerous studies of field/wind tunnel measurements and computational fluid dynamics (CFD) simulations have been undertaken to investigate the flow and pollutant dispersion in two-dimensional (2D) street canyons and three-dimensional (3D) urban-like models. The most significant urban parameters have been regarded as street aspect ratios (building height/street width H/W) for 2D street canyons (Oke, 1988; Meroney et al., 1996; Xie et al., 2006; Li et al., 2009) and building packing densities in 3D urban-like models (Chang and Meroney, 2003; Di Sabatino et al., 2007; Buccolieri et al., 2010; Hang and Li, 2011; Ramponi et al., 2015). Moreover, the other key factors include building height variations (Gu et al., 2011; Hang et al., 2012; Lin et al., 2014), ambient wind direction (Kanda, 2006; Lin et al., 2014; Yassin, 2013), near-road vegetation (Buccolieri et al., 2011; Gromke and Blocken, 2015; Vranckx et al., 2015), overall urban form (Hang et al., 2009, 2015; Yuan et al., 2014), building roof shape (Liu et al., 2015), thermal stratifications and buoyancy force induced by wall heating and solar shading (Xie et al., 2007; Luo and Li, 2011; Allegrini et al., 2014; Dallman et al., 2014; Yang and Li, 2015; Li et al., 2015; Nazarian and Kleissl, 2016; Wang and Li, 2016) etc.

Heavy traffic volumes, unfavourable meteorological conditions, and deep street canyons are usually associated with high vehicular pollutant exposure. Under neutral meteorological conditions, flow patterns in 2D street canyons with a perpendicular approaching wind can be classified into four types depending on street aspect ratios (Oke, 1988; Vardoulakis et al., 2003; Xie et al., 2006; Li et al., 2006, 2009): isolated roughness flow ($H/W < 0.3$), wake interference flow ($0.3 < H/W < 0.7$), skimming flow ($1.67 > H/W > 0.7$), and multi-vortex flow ($H/W > 1.67$). Especially, two counter-rotating vortices have been reported as $H/W = 2$ (Xie et al., 2006) while three to five vertically aligned vortices as $H/W = 3$–5 (Li et al., 2009). Such high-rise deep street canyons with multiple vortices usually experience much more severe street air pollution since it is difficult for the ambient flow to penetrate downwardly into the ground level where vehicular pollutant sources locate. However, these findings are based on the scale of wind-tunnel models with a reference Reynolds number (Re) in order of 10^4 (Xie et al., 2006; Li et al., 2009). To ensure Reynolds number independence in urban turbulent flows, Re should be much greater than 11,000 (Snyder, 1972). By conducting CFD simulations, Zhang et al. (2011) found a single-main-vortex structure in a full-scale street canyon with $H/W = 2.7$ and $Re = 5 \times 10^6$ ($H = 27$ m), which was totally different from the two-main-vortex structure in wind-tunnel-scale models (Xie et al., 2006; Li et al., 2009). Further investigations are still required to confirm the flow pattern in high-rise deep street canyons ($H/W > 2$). In addition, continuously increasing vehicles in urban areas urge the urban planners to construct more viaducts elevating the road from the ground level to mitigate the heavy traffic pressure. Meanwhile, road noise barriers are sometimes constructed on both sides of viaducts to protect near-road residents from the noise caused by traffic. These near-road structures can influence the flow regime and pollutant dispersion in street canyons as well (Hang et al., 2017).

The intake fraction (iF) is defined as the fraction of total emission inhaled by a population. It has been adopted to evaluate the exposure of different population subgroups to traffic-related pollutants in realistic micro-scale street canyons as case studies (Habilomatis and Chaloulakou, 2015; Zhou and Levy, 2008). In addition, daily pollutant exposure (E_t) represents the extent of human beings' contact with specific air pollutants within one day. Ng and Chau (2014) conducted CFD simulations to assess the impact of street setbacks and building permeability on daily carbon monoxide (CO) exposure in idealized street canyons. Recently Hang et al. (2017) introduced iF and E_t into CFD simulations to evaluate how typical medium aspect ratios ($H/W = 1$ to 0.5) and viaduct settings influenced CO exposure in near-road buildings and at pedestrian regions.

Recently, many studies have focused on urban pollutant dispersion of inert particulate matter (Blocken et al., 2016; Lin et al., 2016; Habilomatis and Chaloulakou, 2015) and reactive pollutants such as NOx and O_3 etc (Kwak et al., 2013;Park et al., 2015; Zhong et al., 2015). For inert particle dispersion, the gravity force and deposition effects in related to particle diameters, dynamic wind and thermal buoyancy forces are all significant factors. For reactive pollutants, the coupling processes of turbulent mixing and

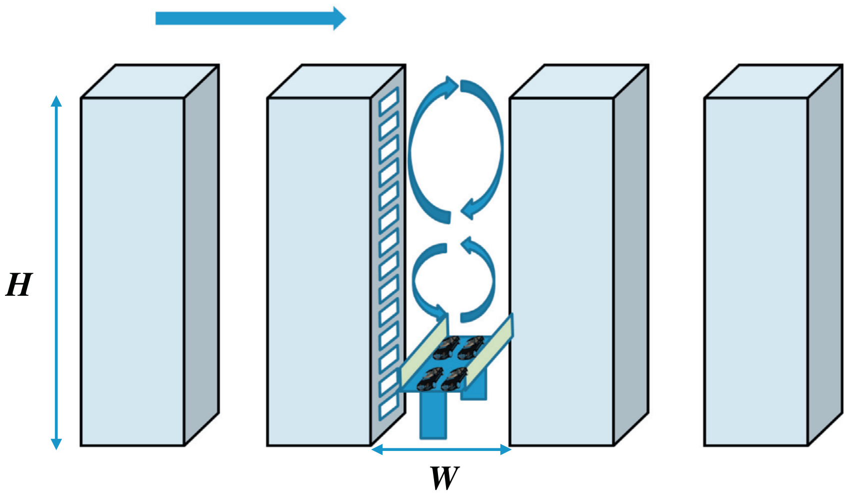

Fig. 1. Sketch of street canyons with viaduct settings and noise barriers.