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Experimental and numerical studies of flows through and within high-rise building arrays and their link to ventilation strategy

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ABSTRACT

Urban ventilation implies that wind from rural areas may supply relatively clean air into urban canopies and distribute rural air within them to help air exchange and pollutant dilution. This paper experimentally and numerically studied such flows through high-rise square building arrays as the approaching rural wind is parallel to the main streets. The street aspect ratio (building height/street width, H/W) is from 2 to 5.3 and the building area (or packing) density (λ_p) is 0.25 or 0.4. Wind speed is found to decrease quickly through high-rise building arrays. For neighbourhood-scale building arrays (1–2 km at full scale), the velocity may stop decreasing near leeward street entries due to vertical downward mixing induced by the wake. Strong shear layer exists near canopy roof levels producing three-dimensional (3D) vortexes in the secondary streets and considerable air exchanges across the boundaries with their surroundings. Building height variations may destroy or deviate 3D canyon vortexes and induced downward mean flow in front of taller buildings and upward flow behind taller buildings. With a power-law approaching wind profile, taller building arrays capture more rural air and experience a stronger wind within the urban canopy if the total street length is effectively limited. Wider streets (or smaller λ_p), and suitable arrangements of building height variations may be good choices to improve the ventilation in high-rise urban areas.

1. Introduction

In high-rise compact urban areas like Hong Kong and Manhattan in New York, urban airflow is generally weak because high-rise building arrays produce strong resistances to the approaching wind, as a result, gaseous pollutants released by vehicle emissions (Fenger, 1999) may stay for a long time within street networks producing traffic air pollution and associated health effects in urban air environments. Wind from the surrounding rural areas may supply relatively clean air into urban canopies and remove airborne pollutants out, so it is important to study how to enhance the capacity of rural wind flowing through high-rise urban areas and how to distribute rural air within such urban canopies more effectively, i.e. improving air exchanges between urban areas and their surrounding rural areas.

Numerical simulations using large-eddy simulation (LES) or RANS (Reynolds-averaged Navier–Stokes equation) turbulence models, wind tunnel and field measurements are important methods to study the flow and dispersion in urban areas. In two-dimensional (2D) street canyon models, street aspect ratios (street height/street width, H/W), roof shapes, etc. are important parameters for pollutant removal and air exchange through the canyon roofs. Oke (1988) and Sini et al. (1996) reported three flow regimes depending on different aspect ratios (street height/street width, H/W), i.e. the isolated roughness flow regime (IRF, in which the aspect ratio is less than 0.1–0.125), the wake interference flow regime (WIF, with an aspect ratio of 0.1–0.67), and the skimming flow regime (SF, with an aspect ratio of 0.67–1.67). Meroney et al. (1996) performed experimental studies of pollutant dispersion in 2D street canyons with these three flow regimes. Xie et al. (2006) and Li et al. (2009) found the fourth flow regime of the multi-vortex regime, i.e. there are two or more vortexes in 2D deep street canyons with aspect ratios of more than 1.67. For such 2D deep canyons, wind near the street ground is weak, and airborne pollutants produced by vehicle emissions are difficult to be removed out through canyon roofs. General urban canopies are three-dimensional (3D) structures. Street aspect ratios, building arrangements, total street length, building area densities (λ_p, i.e. the ratio between the plan area of buildings viewed from above (A_p) and the total underlying surface area (A_d)), frontal area densities (λ_f, i.e. the ratio between the frontal area of buildings facing the wind (A_f) and the total underlying surface area (A_d)) and street orientations (or ambient wind directions), etc. are important urban parameters.

Studies so far on 3D urban canopies mainly focused on the flow and pollutant dispersion around an isolated building (Li and

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Stathopoulos, 1997), in rectangular building arrays (Chang and Meroney, 2001; Chang and Meroney, 2003) and cube or square building arrays with different building area densities (Hanna et al., 2002; Cheng et al., 2003; Lien and Yee, 2004; Di Sabatino et al., 2007; Boppana et al., 2010), in random urban-like obstacles (Xie et al., 2008) and in idealised city models with different overall city forms (Hang et al., 2009). Britter and Hanna (2003), Belcher (2005), Ahmad et al. (2005) and Kanda (2006a) provided some reviews of such studies. As described by Roth (2000) and Belcher (2005), for 3D urban canopies, wind speed decreases due to the drag force by buildings. Wind interacts with buildings and produces strong shear layer at canopy tops, inducing 3D turbulent mixing and converting some fraction of mean kinetic energy into turbulent kinetic energy. Moreover, previous studies mainly emphasised on 3D building arrays with aspect ratios (H/W) of less than 2 and focused on local airflows inside the streets in contrast to those above roof tops. This paper was more interested in 3D high-rise building arrays with aspect ratios of not less than 2, and aimed to investigate how to improve the capacity of the upstream rural wind flowing through such urban canopies in contrast to the upstream rural wind.

Hanna et al. (2002) numerically studied wind conditions in some sparse cube arrays (street aspect ratio $H/W=2/3$, building area density $\lambda_p=0.16$) finding that all flow characteristics approach stream-wise equilibrium state after typically three rows of obstacles. Lien and Yee (2004) investigated airflows in a seven-row cube array ($\lambda_p=0.25$, $H/W=1$), and reported that the mean flow and the turbulence stop decreasing and reach an approximate stream-wise equilibrium since the fourth row. However Lien and Yee (2005) analysed the drag force produced by seven buildings and the results displayed that the drag coefficients for the fourth, fifth and sixth rows differ from each other. Hang and Li (2010) pointed out that stream-wise equilibrium reported in Lien and Yee (2004) is false and wind speed stops decreasing after the fourth row only because the wake behind the cube array may induce downward flows across street roofs and bring some air into the cube array. A real stream-wise equilibrium in building arrays implies that not only the velocity and turbulence stop decreasing, but also the drag forces produced by buildings stop varying. To verify it, Hang and Li (2010) studied seven-row, fourteen-row and twenty-one-row cube arrays ($\lambda_p=0.25$, $H/W=1$), finding that stream-wise equilibrium does not exist in the seven-row array but does appear in the fourteen-row and twenty-one-row arrays. Such process (i.e. stream-wise equilibrium) for high-rise compact building arrays with aspect ratios (H/W) of not less than 2 and building area densities (λ_p) of not less than 0.25 was rarely studied.

In addition, most previous studies concentrated on turbulent flows and pollutant dispersion in urban-type building arrays with parallel approaching winds. Kim and Baik (2004) performed numerical simulations of cube arrays with ambient wind directions of 0°, 15° and 45°. They reported that the capacity of pollutant removal decreases when the incident wind angle increases. Hang et al. (2009) studied pollutant dispersion in idealised round city models with ambient wind directions of 0°, 15°, 30° and 45°. They found that small incident wind angles of 0° and 15° are better for the pollutant removal and air exchange than large incident angles of 30°

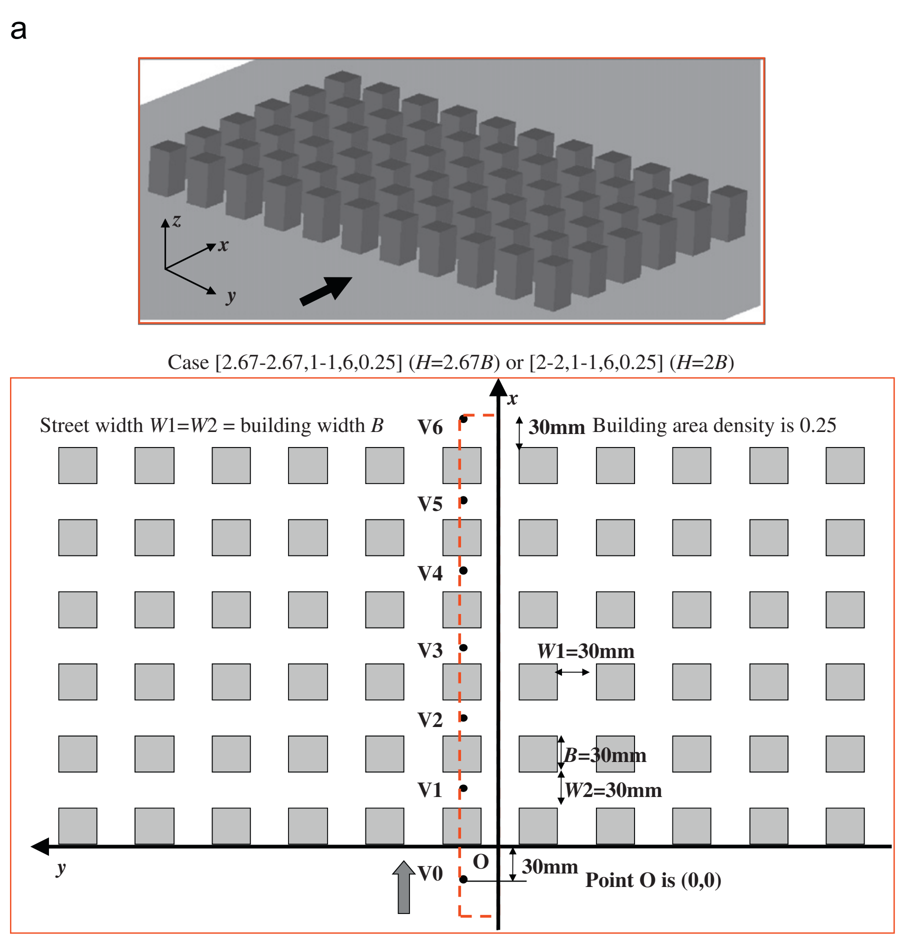

Fig. 1. Model descriptions in wind tunnel tests: (a) Medium arrays with uniform heights in Case [2-2, 1-1, 6, 0.25] or Case [2.67-2.67, 1-1, 6, 0.25], (b) a medium array with a building height variation in Case [2-2.67, 1-1, 9, 0.25], (c) a packed array in Case [2.67-2.67, 0.5-0.67, 9, 0.4]. (d) A hotwire in wind tunnel measurements. (e) Vertical profile of the velocity and turbulence at Point S5 and S5A in Case [2.67-2.67, 0.5-0.67, 9, 0.4] in wind tunnel data. Each case name denotes an aligned square array [$H1/B$-$H2/B$, $W1/B$-$W2/B$, row number, the building area density].