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Wind conditions and ventilation in high-rise long street models

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ABSTRACT

We regarded high-rise cities as obstacles and channels to wind. We first studied wind conditions and ventilations in idealized high-rise long street models experimentally and numerically with a constant street width ($W = 30$ mm), variable street heights ($H = 2\ W, 2.5W, 3W, 4W$), variable street lengths ($L = 47.4W, 79W, 333W, 667W$) and a parallel approaching wind. The flow rates penetrating into windward entries are a little larger than the reference flow rate in the far upstream free flow through the same area with windward entries in all models. The stream-wise velocity decreases along the street as some air leaves upwardly across street roofs. Near the leeward entry, there is a downward flow which brings some air into the street and results in an accelerating process. In the neighborhood scale long streets ($L = 47.4W$ and $79W$), wind in taller streets is stronger and the ventilation is better than a lower one. For the city scale long streets ($L = 333W$ and $667W$), a constant flow region exists where the vertical velocity is zero and the stream-wise velocity remains constant. In such regions, turbulent fluctuations across the street roof are more important to air exchange than vertical mean flows. In a taller street, the process to establish the constant flow conditions is longer and the normalized balanced horizontal flow rate is smaller than those in a lower street. In the city scale long streets, the turbulence exchange rate can be 5–10 times greater than the mean flow rate.

1. Introduction

Wind conditions in urban areas are very important in removing or dispersing the airborne pollutants in urban canopies or providing cleaner external (rural) air. In the main urban areas of Hong Kong such as North Point, Causeway Bay, Central, and Sheung Wan (see Fig. A1 in Appendix A), the street aspect ratio (building height/street width, i.e. H/W) is mostly more than 2–4, sometimes exceeds 6 and even reaches 10. The easterly prevailing wind in the atmospheric boundary layer (ABL) may be seriously blocked in such packed high-rise urban areas. A fraction of air may be driven out of the high-rise urban canopy (see Fig. A2a).

Britter and Hanna [1] summarized studies of the flow in urban areas into four scales, i.e. the regional scale (up to 100 or 200 km), the city scale (up to 10 or 20 km), the neighborhood scale (up to 1 or 2 km) and the street scale (less than 100–200 m). The regional scale [2] regards a city as a roughness of the atmosphere boundary layer and emphasizes the regional effect of geographic and meteorological conditions on urban wind environment and regional pollutant transportation in a large scale. The minimum grid size is several hundred meters without any flow information in a street/building scale. Many investigations study the local turbulent flow in a street scale or in a neighborhood scale, i.e. around isolated buildings [3], in low-rise [4–6] and high-rise street canyon models [7,8] and within finite groups of buildings [9–12]. These studies used experimental measurements and/or numerical simulations by large-eddy simulation (LES) or by Reynolds-averaged Navier–Stokes (RANS) turbulence models, as reviewed by previous researchers [1,13,14].

Our ultimate aim is to study wind conditions in a high-rise packed city like Hong Kong in a city scale (up to 10 km). General numerical techniques have difficulty in studying urban airflows in a city scale because simulating airflows around thousands of buildings requires an unaffordable grid number. For example, a high-rise building array in a neighborhood scale with hundreds of buildings generally requires tens of millions of grids and that in a city scale with thousands of buildings requires billions of grids. We regard the city with high-rise buildings and narrow streets as blockages and pathways to the approaching wind. In this paper, we first study wind conditions in high-rise long street models in a neighborhood scale and in a city scale with a parallel approaching wind (see Fig. A2a and b). In addition, the grid number in long street models can be technically reduced because there are no secondary streets and the grid size along the long street can be

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large where the stream-wise gradients of flow variables is small. The difference between these two models is that there are no building height variations and no interactions at street intersections in the long street model.

When the street is long in contrast to its width and the approaching wind is perpendicular to the street axis, the flow can be treated as two-dimensional (2D). Many studies were performed to study different vortex structures in different 2D street canyons [4–8], probably because that the pollutants tend to stay a relatively long time in such situation. Actually if the street is very long with a parallel approaching wind, the pollutants may accumulate along the street and the air in its downstream region may also be seriously polluted. Soulhac et al. [15] developed a theoretical model for studying wind profile in low-rise long streets ($H/W = 1$ or 2) with a parallel approaching wind. The long street models in this study were assumed to be embedded in the fully developed region of a long city and subsequently there were no end effects. Hang et al. [16] performed both wind tunnel measurements and numerical simulations to study the flow mechanism and ventilation flow rates through a low-rise long street model ($H/W = 1$, $L/W = 22$). It was found that a flow balance may exist in a very long low-rise street when the vertical velocity component is nearly equal to zero and its horizontal flow rate is a constant. When wind is blowing at angle which is not parallel or perpendicular to the street axis, a helical flow structure can be observed along the street [14,15]; i.e. a combination of a longitudinal flow along the street and a mixing recirculation flow.

This paper focuses on wind conditions and ventilation in the high-rise long street models when the approaching wind is parallel to the street axis. The street aspect ratios are more than 2 and the street length is from a neighborhood scale to a city scale. We are more interested in what happens in a city scale long street. For example, the east-westerly straight Chang-a street in Beijing is 42 km long and some east-westerly streets along Hong Kong Island also reach 10 km. Such long street models would reveal the distance that wind can penetrate into the street, whether the wind can blow through the entire long street or it may stop at somewhere, and what is the impact of the building height and the street length.

2. Methodology

Idealized models which consist of five long streets were studied (see Fig. 1a) by assuming that the approaching wind blows parallel to the long streets. In all the idealized models, the width of streets (W) and width of buildings (B) are kept constant ($W = 30$ mm, $B = 40$ mm), but the uniform height (H) of streets and length (L) of streets vary in which the street aspect ratio (H/W) is 2, 2.5, 3 or 4, and street length ratio (L/W) is 47.4, 79, 333 or 667. Computational fluid dynamic (CFD) simulations were carried out to reproduce those wind tunnel tests. These models are in 1:500 to the full scale construction, i.e. corresponding to the street width of 15 m and the street length of 0.7 km, 1.2 km, 5 km or 10 km at the full scale. The two length scales of 47.4W and 79W (or 0.7 km and 1.2 km at the full scale) belong to the neighborhood scale, and the other two scales of 333W and 667W (or 5 km and 10 km at the full scale) correspond to the city scale. There are totally 16 test cases. The cases are described by Long [aspect ratio H/W, the street length ratio L/W]. That is, Long [2, 47.4] will refer to a long street model in which the aspect ratio is 2 and the street length ratio is 47.4. Besides this case, the other 15 cases include Long [2.5, 47.4], Long [3, 47.4], Long [4, 47.4], Long [2, 79], Long [2.5, 79], Long [3, 79], Long [4, 79], and some city scale long street models, i.e. Long [2, 333], Long [2.5, 333], Long [3, 333], Long [4, 333], Long [2, 667], Long [2.5, 667], Long [3, 667], Long [4, 667]. In this study, both CFD simulations and wind tunnel measurements were employed for the neighborhood scale long street models ($L/W = 47.4$ or 79) but for the city scale long street models ($L/W = 333$ or 667), only CFD simulations were performed.

All the measurements were carried out in an aerodynamics boundary layer wind tunnel (closed-circuit type) which is located at the Laboratory of Ventilation and Air Quality, University of Gävle, Sweden. The working section is 11 m long, 3 m wide and 1.5 m high. There was no roughness element on the wind tunnel floor. The velocity and turbulence intensity were measured by a hotwire anemometry. For the measurement at each point, the measuring frequency is 100 Hz and the measurement time is 30 s.

For the idealized models with a length of 47.4W and 79W (i.e. Cases Long [2, 47.4], Long [2.5, 47.4], Long [3, 47.4], Long [4, 47.4], Long [2, 79], Long [2.5, 79], Long [3, 79] and Long [4, 79]), as shown in Fig. 1b, we measured vertical profiles (from wind tunnel floor to a height of 10W above wind tunnel floor) at Point A (in Street A) and Point C (in Street C) (i.e. locating at 15.4W from the leeward street opening of each long street), as well as the horizontal profile along the street axis of Street A at the height of $z = W$ above the wind tunnel floor. Fig. 2 shows that vertical profiles of velocity and turbulence intensity at Point A and Point C are almost the same, so we only put forward the study of street A (surrounded by the dot line in Fig. 1b) in CFD simulations such that symmetric half of Street A domain was adopted so as to reduce calculation time.

For CFD simulations, the CFD code Fluent 6.3 was used with both the standard k-ε[17] and the RNG k-ε turbulence model [18] to solve the incompressible steady and isothermal turbulent flow field. The computation domain in Long [3, 47.4] is shown in Fig. 3a as an example. At the domain inlet, turbulent kinetic energy k and its dissipation rate ε were calculated by vertical profiles of the stream-wise velocity $\overline{u}$(or the velocity V) and turbulence intensity I measured in the far upstream free flow (Fig. 3b), using the equations of $k = 1.5(I\overline{u})^2, \varepsilon = C_\mu^{3/4}k^{3/4}/l_t$, where C_μ is a constant (0.09) and l_t is the turbulent characteristic length scale.

We should note that, the hotwire is only sensitive to velocity components which are perpendicular to it (i.e. the vertical (z) velocity $\overline{w}$ and the stream-wise (x) velocity $\overline{u}$, see Fig. 3c). So the velocity measured by the hotwire is actually the value of $\sqrt{\overline{u}^2 + \overline{w}^2}$. In the upstream free flow, both span-wise ($\overline{v}$) and vertical ($\overline{w}$) velocity components are zero, so the measured stream-wise velocity ($\overline{u}$) equals the local velocity ($V = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}$). Within the long streets, because the hotwire in this study always locates at the street center where the span-wise (y) velocity $\overline{v}$ is zero, the measured velocity components $\sqrt{\overline{u}^2 + \overline{w}^2}$ also equals to the local velocity ($V = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}$).

Fig. 3d shows the grid generation near the long street model of Long [3, 47.4]. The grid size in the stream-wise direction (dx) can be large in regions far from the two street ends where the stream-wise gradients are small. For example, the maximum grid size (dx) is 5W in the city scale long street of Case Long [3, 667]. The number of hexahedral cells generated for all CFD simulations were 151,950 to 258,804. The minimum mesh size near walls was 0.07W where no slip wall boundary condition with standard wall functions [19] was used. We used a zero normal gradient for all boundary variables at the domain outlet, the domain roof and symmetry boundaries.

To quantify the variation of air motion, we normalized stream-wise (x-axis) and vertical (z-axis) velocity components by stream-wise velocity which was measured at the same height of the far upstream plane. Volumetric flow rates through street openings, along the street and across the street roof were used to evaluate the capacity of pollutant dilution and air exchange by wind effect. And a reference flow rate (Q_∞) calculated by Eq. (1) was developed. Then Eq. (1) was used in Eq. (2) for giving the normalized mean flow rates across street openings and the street roof in Eq. (3) to give the normalized effective flow rate due to turbulent exchange