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Impacts of cross-ventilation on the air quality in street canyons with different building arrangements

Fang Yang [a, b], Yongwei Gao [a], Ke Zhong [a, *], Yanming Kang [a, **]

[a] School of Environmental Science and Engineering, Donghua University, Shanghai 201620, China
[b] College of Mechanical Engineering, Shanghai University of Engineering Science, Shanghai 201620, China

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ABSTRACT

The effect of cross-ventilation in buildings on air quality within street canyons is evaluated by employing computational fluid dynamic (CFD) models. The impacts of the airflow entering the canyons through the upstream building windows on flow field and pollutant distribution were investigated in both regular and staggered canyons, and the influences of window-opening-percentage (WOP) for different street width to building height aspect ratios (AR) was studied. The numerical results show that the airflow through the windows of the upstream building can destroy the primary vortex and leads to a new flow pattern within the canyon. When the WOP is increased from 0 to 10%, the ability of the flow for pollutant dilution and dispersion can be improved. This causes the pollutant concentrations decreased by 23% to 27% in the street. And these reductions are greater for staggered arrangements than that for regular arrangements. The influences of the WOP on air flow inside the canyon decrease with increasing the AR. A limiting aspect ratio exists, beyond which the flow structure and the pollutant concentration in the canyon will not be changed no matter what the WOP is.

1. Introduction

Air pollution has become a major problem in most megacities of China because vehicular pollutants are emitted from ground level into streets where are commonly surrounded by high-rise buildings. Studying air flow characteristics and pollutant transport in street canyons has gained importance in recent years [1,2].

Numerous studies including field measurements [2–4], wind tunnel and water channel experiments [5–9] have been conducted to investigate the flow field and pollutant dispersion inside street canyons. In order to describe the air flow and pollutant transportation in urban environment, CFD techniques have been widely used to simulate flow field and pollutant transportation in street canyons [10–29].

Vardoulakis et al. [10], Li et al. [11] and recently Lateb et al. [12] have presented extensive reviews of modeling flow patterns and pollutant dispersion in street canyons. According to all the previous studies, the important factors influencing the flow fields and pollutant distributions in canyons are mostly categorized as followed: geometric conditions of building configuration, such as canyon aspect ratio (i.e., AR, the ratio of street width W to building height H) and building roof geometries, characteristics of the approaching wind (wind speed and direction), thermal effect, tree planting, and traffic-induced turbulence.

An early study to quantify the flow regimes in street canyons was conducted by Oke [13]. The flow pattern was classified into three main regimes based on aspect ratio, i.e., isolated roughness, wake interference and skimming flows. There is one vortex located in the center of the street canyon with AR = 1, which is the most common case to investigate [14,15]. With the decrease of AR, the vortex number may increase [14,15]. For asymmetrical street canyons, the flow structures are more complicated. Xie et al. [16] classified three kinds of vortex characteristics, i.e. one vortex, two co-rotating vortexes and multi-vortex regimes, according to the ratios of H_1/W (ratio of upstream building height to street width) and H_1/H_2 (height ratio of upstream building to downstream building). These features are obtained in 2D simulations. However, the real urban geometries are three dimensional, where the flow structures are different from those in 2D simulations. For instance, results of Hunter [17] indicated that there exist double-eddy circulations behind the upstream buildings. Recently, Shen et al. [18]

* Corresponding author.
** Corresponding author.
E-mail addresses: zhongkeyx@dhu.edu.cn (K. Zhong), ymkang@dhu.edu.cn (Y. Kang).

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introduced five flow types based on the geometrical parameters of the building canopy. They pointed out that the building wake effect is the essential feature for different flow patterns, which is varying with packing density. Chang and Meroney [19] revealed that once the aspect ratio is larger than 5, the flow field appears to be perturbed by individual isolated buildings. Building array and building height variability are also proved to be significant factors in determining flow field and pollutant dispersion from local to neighborhood scale in the urban canopy [20]. Kim and Baik [21] conducted 3D simulations with cubic obstacles through varying wind directions, and identified three flow patterns considering the characteristics of the mean flow circulation generated behind the upwind building.

A preliminary study conducted by Sini [22] revealed that thermal effect plays an important role in changing flow structures in canyons. Xie [23] investigated the single-surface heating effect on the flow patterns and air exchange rate (AER) of the canyons, the results show that the flow structures and AER are strongly influenced by the buoyancy force. Nazarian and Kleissl [24] conducted 3D simulations with realistic non-uniform surface heating, and found that the flow patterns in the canyon are significantly affected by the heating conditions.

Pollutant dispersion in a street canyon mainly depends on the flow patterns. This conclusion has been validated by Li and Stathopoulos [25]. Liu [26] adopted 3D simulations to investigate the pollutant dilution with different ARs. It is shown that more pollutants will be trapped in the street canyon with decrease in AR. Michioka et al. [27] studied the pollutant dispersion mechanisms with different ratio L/H (ratio of building length L to building height H). With smaller ratios, the relative contribution of the turbulent mass flux to the net mass flux was close to unity. This relative contribution decreased with increasing the ratios. Zhang et al. [28] conducted a LES study of pollutant dispersion under real-time wind conditions. The results indicate that real-time wind condition is effective in pollutant dispersion. Tan et al. [29] using uneven street temperature to model surface heating effects. The pollutant dispersion showed different characteristics with varying thermal conditions.

However, buildings flanked around streets were usually simplified as concrete blocks in most of the previous studies [13–29], thus the effects of cross-ventilation through the buildings on the flow fields in the canyons were negligible. This assumption is not always appropriate in practice. To improve indoor air environment, residents living in buildings are likely to open windows for cross-ventilation, this leads to a large amount of airflow entering the street through the windows, and the airflow would distort the flow patterns in the canyon.

Some investigations have been conducted to study the natural ventilation in buildings in the vicinity of streets [30–35]. These studies considered the effects of outdoor air on either building ventilation performances [32,33] or air flow indoors [34,35]. However, when room natural ventilation occurs, the effects of the window-opening-percentage (i.e., the WOP, which is defined as the ratio of the building windows' opening area to the total facade area) on the flow fields and pollutant transportations inside the canyons have not be appropriately considered up to now.

The aim of this study is to evaluate the impacts of window openings on flow structures and pollutant dispersions within street canyons by using three-dimensional numerical simulations. Two street canyon configurations, i.e., the regular and staggered arrangements [7,36], are considered with different WOPs, and the CFD code FLUENT-6.3.26 is employed to perform the simulations. The influences of the WOP on the airflow patterns and air qualities in both the regular and staggered canyons are analyzed by using the numerical results.

2. Model set-up and validation

2.1. Computational domain, grids and numerical scheme

Fig. 1 shows schematics of the two canyon geometrical configurations [36]. To simplify the simulations, all building models are set to be 15 m wide (B), 15 m high (H) and 66 m long (L), and the buildings are infinitely repeated in the y-direction (Fig. 1(a)). Building models are placed at a separation distance S in perpendicular to the wind direction, and two values of S, 10 m and 20 m, are used for the simulations. To study the effects of the WOP on the flow and pollutant fields in the canyon, seven cases of the street width, i.e., $W = 30$ m, 40 m, 50 m, 60 m, 70 m, 80 m and 90 m, are used, and the corresponding street width to building height aspect ratios (AR $= W/H$) are 2, 2.67, 3.33, 4, 4.67, 5.33 and 6, respectively.

Considering many buildings around a canyon are office or dorm buildings, two identical rooms are aligned on each side of the buildings [37], and these buildings are all five-storey buildings and 20 rooms on each floor (Fig. 1(b)). To take into account the impact of cross-ventilation in buildings on air flow and pollutant dispersion in the canyon, the windows of the 30 rooms on the first, third and fifth floors (i.e., 10 for each floor) of each building are set to be partially opened to allow natural ventilation, while all the windows on the second and fourth floors are completely closed. The rooms with opening windows are sized at $l \times b \times h = 15\text{ m} \times 3\text{ m} \times 3\text{ m}$, and an inner wall is installed at the middle of each room (Fig. 1(c)).

The airflow patterns inside and above the street canyon are symmetric to the middle section of the buildings and the street channels when the prevailing wind flow is perpendicular to the street. For reducing the numerical simulation cost, the model domain can just cover a basic portion of the repeated buildings by adopting symmetric boundary conditions on the lateral sides of the domain, as identified with a dashed area in Fig. 1(a). In the CFD models, the inlet, outlet and top of the computational domain are set at $8H$, $28H$ and $6.6H$ away from the street canyon boundaries, respectively. These positions are sufficiently far away from the canyon so that the intervention of these physical boundaries can be avoided [38–41]. Moreover, CO is chosen as a representative of traffic emission due to it is relatively stable, and comes mainly from vehicular exhaust in the canyon [4,42]. The emission source is treated as a volume source with a total length of the domain in the middle of the street from $z = 0$ to $z = 0.5$ m. The width of the source is 10 m and its length is the entire computational domain length $(L + S)/2$, see Fig. 1(a). The emission rate of the pollutant is set at $q_0 = 5 \times 10^{-4}$ kg/(m·s). To determine the impacts of the WOP on airflow and pollutant dispersion between indoor and outdoor air, WOP = 1%, 3%, 5% and 10% are used in the simulations, respectively.

To conduct the simulations, a grid sensitivity analysis was performed to ensure the accuracy of the numerical results. The computational domain was discretized by using tetrahedral elements. Fine grids were used in the vicinity of building walls and the ground, and then the grids become coarser away from these solid surfaces. Grid convergence was estimated by using the concept of Grid Convergence Index (i.e., GCI) [43,44]. Three grid systems (coarse, normal and fine) were used for simulating the flow field and pollutant distribution. Coarsening and refining were conducted by varying the grid size and expansion ratio between adjacent grids. Simulations on the three grid systems of a regular canyon have been performed with WOP = 10% at $S = 10$ m and with increasing W from 30 m to 90 m. The results on the three grids were compared in terms of the dimensionless pollutant concentrations. The comparisons have been made along three vertical lines at the building symmetric plane near the leeward wall (0.5 m from the leeward wall), canyon center and windward wall (0.5 m from the windward wall). The root-mean-square of the relative error