Effects of void deck on the airflow and pollutant dispersion in 3D street canyons

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Abstract
In general, urban canyons are the areas most clearly affected by traffic pollutants since the ability of the canyon to self-ventilate is inhibited due to blockage of buildings or other urban structures. However, previous studies have aimed to improve the pedestrian-level wind speed with void deck in single buildings or short canyons. This study investigated the effects of void deck height and location, and the building height on the airflow field and the traffic pollutant diffusion in a long canyon with $L/H = 10$, validated by wind-tunnel experiment data. The results show that the void decks have a significant effect on the airflow and pollutant distribution inside the canyon. Air exchange rates ($ACH$) of the canyons with the void deck are much larger than that of regular canyons, and the perturbation changes of turbulence ($ACH^\prime$) decrease. For the windward void deck, purging flow rate ($PFR$) and normalized net escape velocity ($NEV^*$) increase by 6.4 times compared to the regular canyon, and for the leeward void deck, increase by 13 times. In particular, when the void decks are at both buildings, they are increased by 38.3 times. Also, for the canyons with the void deck, traffic pollutants are removed out of the canyon by the strong airflow through the void deck. Therefore, unlike the regular canyons, as the void deck and the building height increases, the strength of the airflow through the void deck becomes stronger, and as a result, the mean pollutant concentration is significantly reduced at both walls and the pedestrian respiration level. The mean pollutant concentration on the wall of the building with the void deck and on the pedestrian respiration plane close to it is near zero. These findings can help ease traffic pollution inside the street canyons composed of high-rise buildings, especially in tropical cities.

Keywords Airflow · CFD · Void deck · Street canyon · Traffic pollutant dispersion

Introduction
Today’s urban streets are becoming more and more high-density and high-rise (Zhang et al. 2018a). These compact urban structures form a unique urban climate and affect on the health of citizens (Chew and Norford 2018). In particular, for the street canyons, since the wind speed is relatively low by the blocking effect of urban structures, the influence of vehicle exhaust on pedestrians and near-road residents is very large (Chen and Norford (2017); Yim et al. (2010)). Therefore, many studies have been conducted on airflow and pollutant dispersion inside the street canyons to reduce these adverse effects of traffic pollution emission on people over the past 30 years (Antoniou et al. (2019); Baik et al. (2012); Ricci et al. (2019)). Factors affecting the airflow and pollutant distribution inside the street canyon include wind direction and speed (Huang et al. (2019); Zhang et al. (2018b)), street canyon structure (Cui et al. (2021); Reiminger et al. (2020)) (symmetry, asymmetry), building structure (roof (Huang et al. (2009); Huang et al. (2014); Llaguno-Munitxa et al. (2017)), balcony (Cui et al. (2020); Cui et al. (2021)), void deck (Huang et al. (2020); Huang et al. (2021)), solar radiation (Chew et al. (2018); Mei et al. (2017)), and green infrastructure (Huang et al. (2019); Jeanjean et al. (2015)). Among these factors, the street canyon structure has a great influence on the airflow and pollutant dispersion inside the canyon (Li et al. 2006). Especially, the void deck can greatly increase the pedestrian-level wind speed inside the
canyon (Chen and Mak (2021); Chew and Norford (2019)). The increase of wind speed on the pedestrian-level can lead to good results that can reduce the damage suffered by pedestrians due to the traffic pollutant dispersion. Void deck is the empty space below the “lift-up” building, used for social activities and events (such as weddings) by people in tropical countries such as Malaysia and Singapore. Void deck is generally adopted in building design for the ventilation of street canyons and economic purpose (Moosavi et al. (2014); Muhsin et al. (2017)). However, in the past, void deck received less attention as it was considered undesirable in temperate climates, especially in winter. However, in tropical climates, the outdoor temperature is not low, so that the void deck design is welcomed (Roth and Chow 2012). The residents living in tropical and subtropical hot and humid regions often experience extreme heat stress in summer since the global warming and the urban heat island effect. One way to relieve this thermal stress and improve thermal comfort is to improve the wind speed inside the street canyons. A field study (Yang et al. 2013) in Singapore found that the most effective approach to improve thermal comfort outdoors is to increase wind speed. In Hong Kong, most residents want higher wind speed inside the canyon (Li et al. 2018). As such, with the emergence of many cities in the tropics, the adoption of street canyons with void deck to enhance pedestrian-level wind speed has become fashionable in recent years (Chen and Mak (2021); Huang et al. (2020); Huang et al. (2021); Weerasuriya et al. (2020)).

Huang et al. (2021) conducted the two-dimensional numerical simulation in a symmetric street canyon with a street aspect ratio of 1 and analyzed the effects of various street categories and void deck on the pollutant diffusion. The results show that the void deck has a significant effect on the airflow structure and pollutant diffusion at the vertical central plane of the canyon, and especially when the void deck at both buildings. However, due to the limitations of the 2D numerical analysis, the effect of the void deck and building height, especially the building height, on the pollutant distribution at the canyon walls, and the pedestrian respiration planes, was not disclosed. Chew and Norford (2018) studied the effect of changes in the void deck and building height on the pedestrian-level wind environment in a two-dimensional symmetric street canyon. According to their water channel experiments and numerical simulation results, the change in the void deck height has a significant effect on the pedestrian-level wind speed (up to twice), while the change in the building height has a lesser effect. Also, to enhance the ventilation at the pedestrian level, the height of the void deck 4 m is sufficient. Continuously, they extended their study to the three-dimensional street canyon and revealed that when the void deck height is increased from 2 to 6 m, the pedestrian-level wind speed in the canyon increases from 13 to 59% (Chew and Norford 2019). However, when the building height increases from 24 to 48 m, the increase in pedestrian-level wind speed is lower than 10%. Zhang et al. (2019) investigated the effect of void decks on the first and second floors on the personal intake fraction (P_IF) in deep-short street canyons based on CFD models validated by wind tunnel and scale-model outdoor field experiments. The results show that at H/W = 5, the first floor void deck reduces the personal intake fraction by more than three orders compared to the second floor void deck.

By the above studies, the advantages of the void deck design on the wind environment at the pedestrian-level have been proven. However, the effects of the void deck on the traffic pollutant distribution inside the street canyon have not been clearly identified. Comparisons of the effects of their location, height, and building height on the distribution of traffic pollutant inside 3D street canyons with various void decks have not been reported yet. Also, the effect of void deck on the traffic pollutant distribution at the pedestrians respiration level and both walls is still unknown. Therefore, further studies are still necessary to clarify the effects of void deck on airflow and pollutant dispersion inside the street canyon. More seriously, low wind speed inside the canyon provides favorable conditions for the spread of the influenza, particularly infectious diseases such as the Coronavirus disease 2019 pandemic (Ahmadi et al. (2020); Pani et al. (2020); Xu et al. (2020)). The void deck structure is a very promising architectural design that can urgently solve various environmental problems (vehicle exhaust, heat stress, infectious diseases) and provide a comfortable living environment in the street canyons of the tropical area today.

For the purpose of safeguarding the health of pedestrians and near-road residents, this study provides an insightful understanding of the effects of void deck on the traffic pollutant diffusion inside the street canyons. Fourteen street canyon configurations are chosen to investigate the effects of void deck on airflow and pollutant dispersion under vertical incoming wind. This paper is organized as follows: Fourteen street canyon configurations with and without void deck are given in the “STREET CANYON CONFIGURATIONS” section. Besides, the governing equations for flow and pollutant dispersion, the computational domain, and the boundary conditions which are used for CFD simulation are defined in the “CFD MODEL” section. In addition, the validation study between the numerical results and the WT experimental dataset reported by Kastner-Klein (1999) is performed in the “GRID INDEPENDENCE ANALYSIS” section and the “MODEL VALIDATION” section. The validated CFD models are used to simulate the airflow and traffic pollutant distribution inside the street canyons with and without void deck under the vertical incoming wind. In the “RESULTS AND DISCUSSION” section, numerical results and discussions are presented. The simulation results are used to evaluate the airflow field and pollutant distribution inside the canyons with the void deck,
and to quantitatively assess the effects of the void deck on pedestrians and near-road residents. Especially, to quantify the ventilation capacity of fourteen canyons with the void deck, two ventilation capability indices are adopted. Finally, the “Conclusions” section draws several conclusions.

**Methodology**

In this work, based on an 1:150-scaled isolated street canyon model used in WT experiment conducted at University of Karlsruhe University, Germany Kastner-Klein (1999), 3D street canyons with and without void deck are constructed and validated.

**Street canyon configurations**

Figure 1 shows a sketch of the three-dimensional regular street canyon configuration adopted in this work. As shown in Fig. 1, the regular street canyon is composed of four-lane roads located at the floor of the space between two identical buildings arranged in parallel with each other and two sidewalks on both sides of the canyon. The dimension of each building is set as $H \times H \times 10H$ (where $H = 0.12$ m at the full scale). The height, width, and length of the street canyon are the same as that of the building. That is, a wide and long street canyon with $H/W = 1$, $L/H = 10$ is employed as the regular canyon. In Fig. 1a, $x$, $y$, and $z$ represent the incoming wind direction, canyon direction, and sky direction, respectively, in a three-dimensional Cartesian coordinate system with the origin $(x = 0, y = 0, z = 0)$ at the center of the canyon floor. Also, as shown in Fig. 1b, four line sources have the same dimensions, are arranged in parallel, and continuously emit the tracer gas to mimic the exhaust gas emitted by the four-lane roads. To ensure consistency with the wind-tunnel experiments performed by Kastner-Klein (1999) in model validation, sulfur hexafluoride ($\text{SF}_6$) is used as the tracer gas in this study. To account vehicle exhaust emissions from transverse intersections, four line sources are extended beyond the canyon end by 0.92$H$ on both sides (i.e., the length of each line source is $11.84H$, see Fig. 1a) (Salim et al. 2011a). In addition, to clearly clarify the pedestrian exposure risk to pollutants inside the street canyons, the pedestrian respiration height in each case is set to $H/12$ (1.5 m at the full scale) as in Huang et al. (2019) (see Fig. 1b). The wind approaches vertically to the 3D street canyon.

With considering the change of the building height ($H_b$), the height ($H_v$) and location of void decks, fourteen CFD simulation cases (two cases for regular canyons and twelve cases for the canyons with various void decks) are included in this research. Here, the void deck height is set to $H_v/6$ and $H_v/4$ (3 m and 4.5 m at the full scale) referring to Chew and Norford (2018). Based on the regular street canyon configuration, six canyons with various void decks ($H_v/W = 1/6$) are shown in Fig. 2: canyon with void deck at the leeward building ($H_v/W = 1$, Fig. 2a), canyon with void deck at the windward building ($H_v/W = 1$, Fig. 2b), canyon with void deck at both buildings ($H_v/W = 1$, Fig. 2c), canyon with void deck at the leeward building ($H_v/W = 2$, Fig. 2d), canyon with void deck at the windward building ($H_v/W = 2$, Fig. 2e), canyon with the void deck at both buildings ($H_v/W = 2$, Fig. 2f). Herein, a building with void deck is modeled as an ideal block with an empty space below (Chew and Norford 2019).

**CFD model**

**Governing equations for flow and pollutant dispersion**

The airflow inside the street canyon can be considered incompressible and steady-state turbulent flow. Solar radiation and traffic turbulence are not considered here. Among the common turbulence models, large eddy simulation (LES) often performs better than Reynolds mean Navier-Stokes (RANS) model in predicting air flow and pollutant dispersion (Blocken (2015); Gousseau et al. (2011); Tominaga and Stathopoulos (2011)). However, LES will require more computational resources and present greater challenges in developing advanced sub-grid scale models and specifying an appropriate time-dependent inlet and
wall boundary conditions. Moreover, the steady RANS has unavoidable drawbacks in predicting turbulence, e.g., it does not predict the flow reattachment length behind building and underestimate the velocity in the wake region. Despite these limitations, RANS models (Allegrini et al. (2014); Chen (2009); Cui et al. (2016); He et al. (2017); Sanchez et al. (2017)) have been well validated and widely used to predict airflow and pollutant dispersion within 2D and 3D urban models. Notably, Chew and Norford (2018) and Hang et al. (2012) reported that the simulation results of the standard $k$-$\varepsilon$ for the simulation on the long street canyon agree better with their experimental results than the RNG $k$-$\varepsilon$ or realizable $k$-$\varepsilon$ simulation results. Therefore, the isothermal RANS equations with the standard $k$-$\varepsilon$ model are adopted in this study.

To assess the dispersion of gaseous pollutants inside the street canyon, the steady-state species transport equation is employed. The equation is the following (Huang et al. 2019):

$$
\frac{\partial C^y}{\partial t} + \nu \frac{\partial C^y}{\partial x} + \omega \frac{\partial C^y}{\partial x} = \frac{\partial}{\partial x} \left( \left( \nu + \frac{\nu_t}{\sigma_{C^y}} \right) \frac{\partial C^y}{\partial x} \right) + \frac{\partial}{\partial y} \left( \left( \nu + \frac{\nu_t}{\sigma_{C^y}} \right) \frac{\partial C^y}{\partial y} \right) + \frac{\partial}{\partial z} \left( \left( \nu + \frac{\nu_t}{\sigma_{C^y}} \right) \frac{\partial C^y}{\partial z} \right) + S_y
$$

### Computational domain and grid generation

The computational fluid dynamics (CFD) models are built and meshed with Gambit 2.4.6. The dimension of the CFD domain follows the recommendations in Tominaga and Stathopoulos (2011): the inlet is $8H$ upstream of the leeward building, while the outlet surface is $19H$ downstream from the windward building, and the top surface is $8H$ from the ground, and the both lateral surfaces are placed at $7H$ from the building side walls, resulting in the domain dimensions of $30H$ (length) $\times$ $24H$ (width) $\times$ $8H$ (height). Figure 3 illustrates the CFD domain of the regular canyon without the void deck. The computational domain was meshed using hexahedral grids and all grid cells are perfectly orthogonal without skewness. The total number of grid cells is approximately 4.6 million for each simulation case. The mesh is coarsened above the canyons, upstream of the leeward building, and downstream of the windward building. The maximum grid increase ratio is limited to 1.08. Inside the canyon and void deck, the grid cells with $\delta x = H/72$, $\delta y = H/12$ and $\delta z = H/72$ are created by using the finer mesh size. Detailed information on the grid sensitivity analysis will be provided in the "GRID INDEPENDENCE ANALYSIS" section.
Boundary conditions and numerical scheme

All CFD simulations are performed by using the commercial CFD code ANSYS-Fluent 14.5. The boundary conditions are the following. At the inlet surface, the atmospheric inlet boundary conditions (vertical profiles of wind velocity, turbulent kinetic energy, and turbulent dissipation rate) are imposed. The inlet profiles of the horizontal wind velocity ($U_z$), turbulent kinetic energy ($k$), and its dissipation rate ($\varepsilon$) are prescribed to match the corresponding experimental conditions, which are given in Eqs. (2)–(4) (Kastner-Klein 1999):

$$\frac{U_z}{U_{ref}} = \left( \frac{z}{z_{ref}} \right)^{0.3}$$  \hspace{1cm} (2)

$$k = \frac{u'^2}{\sqrt{C_u}} \left( 1 - \frac{z_{ref}}{\delta} \right)$$  \hspace{1cm} (3)

$$\varepsilon = \frac{k^2}{C_{nu}} \left( 1 - \frac{z}{\delta} \right)$$  \hspace{1cm} (4)

The outlet is given as a zero-gradient boundary condition. The top and both sides of the domain have a symmetry boundary condition. The ground and all surfaces of building (leeward wall, windward wall, roof) have a no-slip boundary condition. For the line sources, the volume flow rate of the mixture of air and tracer gas is provided. The SIMPLE pressure-velocity coupling and the second-order upwind scheme are adopted in numerical study. Residuals of simulation are kept at 10^{-6} for all parameters.

Grid independence analysis

To estimate the mesh independence, three simulation (including the fine, basic, and coarse mesh) cases are performed for the regular canyon shown in Fig. 1. For these three simulations, the mesh sizes in the dense area (in-canyon) are $H/96$, $H/72$, and $H/48$, respectively (see Table 1). Therefore, fine, basic, and coarse mesh models have 8.2, 4.6 million, and 2.2 million cells, respectively. Figure 4 plots the dimensionless pollutant distribution obtained along three vertical lines ($y/H = 0, 1.26, \text{and } 3.79$) near both walls of the canyon for the three simulation cases. The dimensionless pollutant concentration ($K$) was expressed in dimensionless as follows (Kastner-Klein 1999):

$$K = \frac{CU_{ref}HL}{Q_S}$$  \hspace{1cm} (5)

where $K$ is the dimensionless pollutant concentration, $C$ is the measured volume fraction of SF_6, $U_{ref}$ ($= 4.7 \text{ m/s}$) is the free-stream wind velocity at a reference height $z_{ref}$ ($= 0.12 \text{ m}$), $L$ ($= 1.42 \text{ m}$) is the length of the line source, and $Q_S$ is the source strength. Herein, the standard k-ε turbulence model with turbulent Schmidt number ($Sc_t$) of 0.3 is used (Gromke et al. 2008). For each wall, the vertical lines are 5 mm away from that wall. In Fig. 4a, the difference of $K$ between the basic and coarse grids is large, while the deviation of $K$ becomes very small as increasing the mesh resolution from “basic” to “fine”. The $K$ profiles in Fig. 4b depict negligible differences between the three mesh resolutions. Therefore, the basic mesh of 4.6 million cells is determined to be an independent grid, and all subsequent simulations are performed with this basic independent grid number.

Model validation

From the fact that there is no experimental set for 3D long street canyon with the void deck, we carried out a validation study by using the results of a 3D street canyon (model scale 1:150) used for WT experiments performed at the University of Karlsruhe, Germany. Figures 1 and 3 show the isolated regular canyon configuration with the aspect ratio of 1:1 used in the neutral stratified atmospheric boundary-layer wind tunnel experiment (see the internet database CODASC, HTTPS://WWW.UMWELTAERODYNAMIK.DE/BILDER-ORIGINALE/CODA/CODASC.HTML). According to their wind-tunnel experiment, the incoming wind was perpendicular to the canyon axis, and two parallel buildings ($H_b = W_b = 0.12 \text{ m}$, and $L = 1.2 \text{ m}$) were installed on the tunnel floor. A mixture of air and tracer gas (SF_6) with a flow rate of 1000 ppm was continuously emitted from four line sources to mimic the emission of traffic exhaust gas, and the location of the line sources was about 0.23H, 0.35H, 0.65H, and 0.77H away from the windward wall, respectively. SF_6 concentrations were measured at specific points on both walls of the canyon.

Figure 5 shows that the CFD simulation results with grid number of 4.6 million and $Sc_t = 0.3$ are in good agreement with the WT experimental data, so the selected parameters can ensure the accuracy of the CFD model. To evaluate quantitatively the current CFD model performance, the statistical validation tests were carried out on the dimensionless pollutant concentrations for the leeward wall, windward wall, and combination of leeward and windward walls based on the CFD-simulated and WT-measured results. Here, the normalized mean square error (NMSE), the fractional bias (FB), the fraction of predictions within a factor of two of the observations (FAC2),

Table 1 Characteristics of the grids for the grid-sensitivity analysis

| Cases     | Grid size in the dense area | Cells (million) |
|-----------|----------------------------|-----------------|
| Grid 1 (coarse) | 0.00250 m ($H/48$) | 2.2             |
| Grid 2 (basic)  | 0.00167 m ($H/72$) | 4.6             |
| Grid 3 (fine)   | 0.00125 m ($H/96$) | 8.2             |
and the correlation coefficient \((R)\) are used to evaluate the performance of CFD models. The model acceptance criteria are as follows (Chang and Hanna (2004); Moonen et al. (2013)): \(0.5 < \text{FAC2} < 2, -0.3 < \text{FB} < 0.3, \text{NMSE} < 1.5, 0.7 < \text{MG} < 1.3, \text{VG} < 1.6\) and \(R > 0.8\). From Table 2, it is clear that all statistical indicators are within the acceptable range of model performance.

As shown above, the CFD results are in good agreement with the WT measured data. Thus, the CFD model validated in this study is reliable for simulating airflow and pollutant dispersion inside the street canyons with and without void deck.

### Results and discussion

Herein, the characteristics of airflow and pollutant distribution were investigated inside the street canyons with the void deck based on the model validation conducted above. The boundary conditions and reference parameters used in each simulation are the identical as that of the model validation.

### Assessment for street ventilation

In this section, we evaluate self-ventilation capability of canyons with and without void deck. First, the air exchange rate \((ACH)\) is adopted as the ventilation capability index of the canyon. \(ACH\) which indicates the amount of air exchanged between the street canyon and free atmosphere per unit time has been widely used as an important indicator to evaluate the ventilation capacity of the canyon (Li et al. (2005); Liu et al. (2005); Salim et al. (2011b)). For 3D canyons with the void deck, air exchange takes place at both sides and top of street canyons, and at the interface of the canyon and void deck. Therefore, the \(ACH\) of the canyon with the void deck can be evaluated as follows by modifying the \(ACH\) of the regular canyon (Huang et al. 2019).
where $ACH_{Top}$, $ACH_{Side1}$, $ACH_{Side2}$, $ACH_{Void deck1}$, and $ACH_{Void deck2}$ are the values of $ACH$ at each plane where air exchange occurs, respectively. The positive $ACH$ ($ACH^+$) means air exiting from the canyon, while negative $ACH$ ($ACH^−$) means air entering into the canyon. The $ACH$ at an air exchange plane consists of the mean ($\overline{ACH}$) and turbulence ($ACH'$) components:

$$ACH^+ = (ACH_{Top}^+ + (ACH_{Side1}^+) + (ACH_{Side2}^+) + (ACH_{Void deck1}^+ + (ACH_{Void deck2}^+)$$  \tag{6}

$$ACH^- = (ACH_{Top}^- + (ACH_{Side1}^- + (ACH_{Side2}^-) + (ACH_{Void deck1}^- + (ACH_{Void deck2}^-)$$  \tag{7}

where $ACH_{Top}$, $ACH_{Side1}$, $ACH_{Side2}$, $ACH_{Void deck1}$, and $ACH_{Void deck2}$ are the values of $ACH$ at each plane where air exchange occurs, respectively. The positive $ACH$ ($ACH^+$) means air exiting from the canyon, while negative $ACH$ ($ACH^−$) means air entering into the canyon. The $ACH$ at an air exchange plane consists of the mean ($\overline{ACH}$) and turbulence ($ACH'$) components:

$$ACH = \overline{ACH} + ACH'$$  \tag{8}

where $\overline{ACH}$ and $ACH'$ are induced by exchange by the mean velocity and the velocity fluctuation respectively. The $ACH'$ at each air exchange plane can be written as (Li et al. 2005):

![Comparison of K along three vertical lines on the canyon walls between WT measurement and numerical results; a leeward wall; b windward wall](image-url)
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\[ ACH'_{\text{Top}} = -ACH'_{\text{Top}} = \frac{1}{\sqrt{6}} \int k d \Gamma_1 \] (9)

\[ ACH'_{\text{Side}_1} = -ACH'_{\text{Side}_1} = \frac{1}{\sqrt{6}} \int k d \Gamma_2 \] (10)

\[ ACH'_{\text{Side}_2} = -ACH'_{\text{Side}_2} = \frac{1}{\sqrt{6}} \int k d \Gamma_3 \] (11)

\[ ACH'_{\text{Void deck}_1} = -ACH'_{\text{Void deck}_1} = \frac{1}{\sqrt{6}} \int k d \Gamma_4 \] (12)

\[ ACH'_{\text{Void deck}_2} = -ACH'_{\text{Void deck}_2} = \frac{1}{\sqrt{6}} \int k d \Gamma_5 \] (13)

where \( \Gamma_1 = L \times W \), \( \Gamma_2 = H \times W \), \( \Gamma_3 = H \times L \), \( \Gamma_4 = H_1 \times L \), and \( \Gamma_5 = H_2 \times W \) are the areas of the corresponding air exchange planes. Table 3 and 4 tabulate the positive and negative dimensionless air exchange rate (\( ACH' \)) for the fourteen street canyons with and without void deck. According to the analysis of the air exchange rate of the two regular canyons (\( H/W = 1 \) or 2), the values are 0.16 and 0.11, respectively, which are the minimum values compared to the canyons with the void deck. This means that the void deck has a very positive effect on the ventilation of the canyon by enhancing the airflow and the pollutant diffusion to the outside of the canyon. Also, for the two regular canyons, \( ACH' \) values are 77.3% and 75.5%, respectively, which are higher than that of the canyons with the void deck. This finding proves that the void deck significantly reduces disturbances inside the canyon. The detailed analyses on the effects of void deck on the \( ACH \) of the canyon are as follows.

Firstly, it can find that the void deck greatly improves the ventilation capacity of the canyon. The street canyons with void deck have higher \( ACH \) values than regular canyons without the void deck. Regardless of the height of the building and the void deck, the \( ACH \) of the canyons has the maximum values when the void deck is at both buildings, followed by the canyons with the void deck at the leeward building. For the canyons with the void deck at the windward building, the \( ACH \) values are the smallest. This is obviously related to the basic airflow inflowing to the canyon through the void deck. For example, for the canyon (\( H/W = 1 \)) with void deck (\( H/W = 1/6 \)), when the void deck is at both buildings, the pollutants generated from the canyon floor are removed directly out of the canyon by the strong basic airflow flowing through the void decks located at the bottom of two buildings, so the \( ACH \) value is the largest as 0.29. Also, comparing the \( ACH \) values of the street canyons where the void deck is at the leeward building or the windward building, the air exchange rate of the canyon where the void deck is at the leeward building (0.27) is higher than for the canyon (0.18) with the void deck at the windward building since the strength of the basic airflow passing through the canyon is clearly stronger when the void deck is at the leeward building. Specifically, for the canyons with the void deck at the leeward building (\( H/W = 1 \)), the \( ACH \) values are zero at both sides of the canyon. This means that for the canyons with the void deck at the leeward building, there are no airflow components inflowing from both sides of the canyon. These features of three basic airflows have the opposite effect on the perturbation change of the turbulence. In other words, the \( ACH' \) value of the canyon with the smallest basic airflow strength (when the void deck is located at the windward building) is the largest, followed by the canyon where the void deck is located at the leeward building. Among the twelve canyons with void deck, the canyons (\( H/W = 1 \)) with void deck (\( H/W = 1/4 \)) at both buildings have the highest air exchange rate (0.38). When the void deck (\( H/W = 1/6 \)) is at the windward building (\( H/W = 2 \)), the \( ACH \) value is the smallest (0.12).

Secondly, the increase of the void deck height results in the increase of the ventilation capacity of the canyon. As the void deck height increases, the velocity of the basic airflow inflowing to the canyon through the void deck increases, and this strengthened airflow removes more pollutants out of the canyon, thus increasing the canyon’s \( ACH \) value. Conversely, the perturbation change of the turbulence inside the canyon is suppressed that much, and the \( ACH' \) value is reduced.

Thirdly, the ventilation capacity of the street canyons with the void deck reduces as the building height increases. For the regular canyons without the void deck, the \( ACH \) value (0.11) of the regular canyon (\( H/W = 1 \)) is lower than that (0.16) of the regular canyon (\( H/W = 1 \)). This is because the higher the building height, the less free-stream through the canyon top can affect the bottom of the canyon where the pollutants are generated. For the canyons with the void deck, the higher the building height, the stronger the airflow inflowing to the canyon through the void deck, so more pollutants are removed out of the canyon. However, as the building height increases, the canyon volume increases, resulting in a smaller \( ACH \). Therefore, other indicators, purging flow rate (PFR) and normalized net escape velocity (NEV*), are employed in this study. A larger PFR generally depicts that the street canyon is more effectively ventilated, which is described by Yang et al. (2020), as follows:

\[ PFR = S \times \frac{V}{< c >} \] (14)

where \( S \) is the pollutant emission rate, \( V \) and \( < c > \) represent the canyon volume and spatially mean pollution.
### Table 3 Positive dimensionless air exchange rate (ACH+) for the street canyons with the void deck

| Cases                         | ACH<sub>Top</sub> + (V/T) | ACH<sub>Top</sub> + (V/T) | ACH<sub>Side1</sub> + (V/T) | ACH<sub>Side1</sub> + (V/T) | ACH<sub>Side2</sub> + (V/T) | ACH<sub>Side2</sub> + (V/T) | ACH<sub>Void deck1</sub> + (V/T) | ACH<sub>Void deck1</sub> + (V/T) |
|-------------------------------|--------------------------|--------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------------|--------------------------------|
| Regular canyon (H/W = 1)      | 0.0333                   | 0.1053                   | 0.0020                      | 0.0108                      | 0.0020                      | 0.0108                      | -----                          | -----                          |
| Void deck (H/6) Leeward side  | 0.0908                   | 0.1217                   | 0.0142                      | 0.0093                      | 0.0142                      | 0.0093                      | 0.0000                         | 0.0107                         |
| Windward side                 | 0.0485                   | 0.0915                   | 0.0030                      | 0.0104                      | 0.0030                      | 0.0104                      | -----                          | -----                          |
| Both side                     | 0.0329                   | 0.1190                   | 0.0066                      | 0.0094                      | 0.0066                      | 0.0094                      | 0.0000                         | 0.0111                         |
| Void deck (H/4) Leeward side  | 0.1384                   | 0.1177                   | 0.0207                      | 0.0089                      | 0.0207                      | 0.0089                      | 0.0000                         | 0.0200                         |
| Windward side                 | 0.0590                   | 0.0879                   | 0.0037                      | 0.0101                      | 0.0037                      | 0.0101                      | -----                          | -----                          |
| Both side                     | 0.0301                   | 0.1205                   | 0.0075                      | 0.0093                      | 0.0075                      | 0.0093                      | 0.0000                         | 0.0212                         |
| Regular canyon (H/W = 2)      | 0.0200                   | 0.0622                   | 0.0036                      | 0.0107                      | 0.0036                      | 0.0107                      | -----                          | -----                          |
| Void deck (H/6) Leeward side  | 0.0483                   | 0.0672                   | 0.0118                      | 0.0112                      | 0.0112                      | 0.0112                      | 0.0000                         | 0.0072                         |
| Windward side                 | 0.0364                   | 0.0486                   | 0.0073                      | 0.0094                      | 0.0073                      | 0.0094                      | -----                          | -----                          |
| Both side                     | 0.0251                   | 0.0642                   | 0.0064                      | 0.0118                      | 0.0064                      | 0.0118                      | 0.0000                         | 0.0072                         |
| Void deck (H/4) Leeward side  | 0.0735                   | 0.0672                   | 0.0173                      | 0.0113                      | 0.0173                      | 0.0113                      | 0.0000                         | 0.0140                         |
| Windward side                 | 0.0447                   | 0.0437                   | 0.0095                      | 0.0086                      | 0.0095                      | 0.0086                      | -----                          | -----                          |
| Both side                     | 0.0289                   | 0.0642                   | 0.0080                      | 0.0122                      | 0.0080                      | 0.0122                      | 0.0000                         | 0.0143                         |

| Cases                         | ACH<sub>Void deck1</sub> + (V/T) | ACH<sub>Void deck1</sub> + (V/T) | ACH<sub>Void deck1</sub> + (V/T) | ACH<sub> void deck2</sub> + (V/T) | ACH<sub>Void deck2</sub> + (V/T) | ACH<sub> void deck2</sub> + (V/T) | ACH<sub> + /ACH</sub> | ACH<sub> + /ACH</sub> |
|-------------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------------|--------------------------------|--------------------------------|----------------------|----------------------|
| Regular canyon (H/W = 1)      | -----                       | -----                       | -----                       | 0.0372                          | 0.1269                          | 0.1642                          | 22.7%                | 77.3%                |
| Void deck (H/6) Leeward side  | -----                       | -----                       | -----                       | 0.1193                          | 0.1511                          | 0.2704                          | 44.1%                | 55.9%                |
| Windward side                 | 0.0026                      | 0.0056                      | 0.0572                      | 0.1179                          | 0.1751                          | 43.2%                          | 67.3%                | 46.4%                |
| Both side                     | 0.0854                      | 0.0108                      | 0.1315                      | 0.1596                          | 0.2911                          | 45.2%                          | 54.8%                | 46.4%                |
| Void deck (H/4) Leeward side  | -----                       | -----                       | -----                       | 0.1797                          | 0.1555                          | 0.3352                          | 53.6%                | 46.4%                |
| Windward side                 | 0.0041                      | 0.0096                      | 0.0706                      | 0.1177                          | 0.1882                          | 37.5%                          | 62.5%                | 46.4%                |
| Both side                     | 0.1513                      | 0.0190                      | 0.1964                      | 0.1793                          | 0.3757                          | 52.3%                          | 47.7%                | 55.9%                |
| Regular canyon (H/W = 2)      | -----                       | -----                       | -----                       | 0.0272                          | 0.0836                          | 0.1108                          | 24.5%                | 75.5%                |
| Void deck (H/6) Leeward side  | -----                       | -----                       | -----                       | 0.0718                          | 0.0967                          | 0.1686                          | 42.6%                | 57.4%                |
| Windward side                 | 0.0000                      | 0.0035                      | 0.0509                      | 0.0710                          | 0.1219                          | 41.8%                          | 58.2%                | 47.7%                |
| Both side                     | 0.0464                      | 0.0056                      | 0.0843                      | 0.1007                          | 0.1850                          | 45.6%                          | 54.4%                | 47.7%                |
| Void deck (H/4) Leeward side  | -----                       | -----                       | -----                       | 0.1082                          | 0.1038                          | 0.2120                          | 51.0%                | 49.0%                |
| Windward side                 | 0.0000                      | 0.0065                      | 0.0637                      | 0.0673                          | 0.1310                          | 48.6%                          | 51.4%                | 49.0%                |
| Both side                     | 0.0795                      | 0.0106                      | 0.1243                      | 0.1135                          | 0.2379                          | 52.3%                          | 47.7%                | 54.4%                |
Table 4  Negative dimensionless air exchange rate ($ACH^-$) for the street canyons with void deck

| Cases                              | $ACH_{Top} - (V/T)$ | $ACH_{Top}^\prime - (V/T)$ | $ACH_{Side} - (V/T)$ | $ACH_{Side}^\prime - (V/T)$ | $ACH_{Top}^\prime - (V/T)$ | $ACH_{Top} - (V/T)$ | $ACH_{Side}^\prime - (V/T)$ | $ACH_{Side} - (V/T)$ | $ACH_{ Void deck 1} - (V/T)$ | $ACH_{ Void deck 2} - (V/T)$ | $ACH_{ Void deck 2} - (V/T)$ | $ACH_{ Void deck 1} - (V/T)$ | $ACH_{ Void deck 1} - (V/T)$ |
|------------------------------------|---------------------|-----------------------------|----------------------|-----------------------------|-----------------------------|-----------------------|-----------------------------|-----------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Regular canyon ($H/W = 1$)        | −0.0212             | −0.1053                     | −0.0083              | −0.0108                     | −0.0083                     | −0.108                | −0.0083                     | −0.108                | −0.0377                     | −0.1269                     | −0.1646                     | 22.9%                       | 77.1%                       |
| Void deck ($H/6$) Leeward side    | −0.0089             | −0.1217                     | −0.0000              | −0.0093                     | −0.0000                     | −0.1128               | −0.0093                     | −0.1128               | −0.0093                     | −0.1217                     | −0.1511                     | 44.6%                       | 55.4%                       |
| Windward side                     | −0.0120             | −0.0915                     | −0.0042              | −0.0104                     | −0.0042                     | −0.1124               | −0.0042                     | −0.1124               | −0.0090                     | −0.1177                     | −0.1744                     | 33.6%                       | 66.4%                       |
| Both side                         | −0.0058             | −0.1190                     | −0.0056              | −0.0094                     | −0.0056                     | −0.1176               | −0.0056                     | −0.1176               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Void deck ($H/4$) Leeward side    | −0.0109             | −0.1177                     | −0.0000              | −0.0089                     | −0.0000                     | −0.1079               | −0.0000                     | −0.1079               | −0.0090                     | −0.1714                     | −0.1714                     | 33.6%                       | 66.4%                       |
| Windward side                     | −0.0101             | −0.0879                     | −0.0023              | −0.0101                     | −0.0023                     | −0.1079               | −0.0023                     | −0.1079               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Both side                         | −0.0054             | −0.1205                     | −0.0045              | −0.0093                     | −0.0045                     | −0.1079               | −0.0093                     | −0.1079               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Regular canyon ($H/W = 2$)        | −0.0245             | −0.0622                     | −0.0015              | −0.0107                     | −0.0015                     | −0.1071               | −0.0015                     | −0.1071               | −0.0090                     | −0.1714                     | −0.1714                     | 33.6%                       | 66.4%                       |
| Void deck ($H/6$) Leeward side    | −0.0010             | −0.0672                     | −0.0007              | −0.0112                     | −0.0007                     | −0.0711               | −0.0007                     | −0.0711               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Windward side                     | −0.0115             | −0.0486                     | −0.0005              | −0.0094                     | −0.0005                     | −0.0944               | −0.0005                     | −0.0944               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Both side                         | −0.0048             | −0.0642                     | −0.0047              | −0.0118                     | −0.0047                     | −0.0715               | −0.0047                     | −0.0715               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Void deck ($H/4$) Leeward side    | −0.0017             | −0.0672                     | −0.0001              | −0.0113                     | −0.0001                     | −0.1079               | −0.0001                     | −0.1079               | −0.0090                     | −0.1714                     | −0.1714                     | 33.6%                       | 66.4%                       |
| Windward side                     | −0.0064             | −0.0437                     | −0.0002              | −0.0086                     | −0.0002                     | −0.086                | −0.0002                     | −0.086                | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
| Both side                         | −0.0049             | −0.0642                     | −0.0055              | −0.0122                     | −0.0055                     | −0.1102               | −0.0055                     | −0.1102               | −0.0090                     | −0.1714                     | −0.1714                     | 45.7%                       | 54.3%                       |
The building height change significantly increases with the void deck. For the regular canyons, the \( PFR \) and \( NEV^* \) of the canyon with \( H/W = 2 \) are lower than that of the canyon with \( H/W = 1 \). This means that as the building height increases, the ventilation capability of the canyon deteriorates. However, the \( PFR \) and \( NEV^* \) of canyons with void deck are significantly increased compared to the regular canyons. The \( PFR \) and \( NEV^* \) of the canyons with void deck at both sides are the highest (up to 38.3 times of regular canyon), followed by the leeward void deck (up to 13 times of regular canyon). For the canyons with the windward void deck, the \( PFR \) and \( NEV^* \) are the lowest (increase up to 6.4 times of regular canyon) because the weak airflow enters the canyon through the void deck (see Figs. 8 and 9). Also, it can be seen from Fig. 6 that \( PFR \) and \( NEV^* \) of the canyons increase as the void deck height increases under the same building height. For the windward void deck at two building heights (\( H/W = 1 \) and 2), the effect of the void deck height is small (increase 110%), but for the void deck on both sides, it is the largest (160%). In addition, under the same void deck height, the building height change significantly increases the \( PFR \) and \( NEV^* \) of the canyon. For the case of \( H/W = 1/6 \), the \( PFR \) and \( NEV^* \) increase by 360% for the canyons with the windward void deck and 220% for the leeward and both void decks as the building height increases. For the case of \( H/W = 1/4 \), the raised building height increase \( PFR \) and \( NEV^* \) by 280% for the canyons with the windward void deck and 210% for the leeward and both void decks. That is, the building height effect is dominant at the lower void deck height (\( H/W = 1/6 \)). These results mean that the change in the building height plays a more significant role than the change in the void deck height for improving the ventilation capability of the canyon.

From the above analysis, it can find that the ventilation capability of the canyon with void decks is large with the higher building height and higher the void deck height. In particular, the ventilation capability of the canyon with the void deck at both buildings has the highest, followed by the canyons with upwind void deck.

### Airflow and pollutant distributions on the vertical central plane

In this section, the effects of change in the different location (when the void deck is at the leeward building, windward building, or both buildings) and height (\( H/W = 1/6 \) or \( 1/4 \)) of the void deck on the airflow and pollutant distributions of the vertical central plane inside the canyons (\( H/W = 1 \) or 2) are investigated. Figure 7 depicts the airflow patterns and dimensionless pollutant distributions on the vertical central plane of the regular canyons without the void deck. For the regular canyon (\( H/W = 1 \)) (see Fig. 7a), a large clockwise vortex is formed inside the canyon. This vortex is generated by free-stream passing above the canyon. The core of this vortex is slightly upward and to the right from the center of the canyon, and the airflow speed at the core of the vortex is weaker than at the building walls or the ground. The velocity of the downflow on the windward wall is faster than the level.
flow near the ground or the upflow on the leeward wall. Due to this large vortex, many pollutants are accumulated on the leeward side of the canyon, and the pollutant concentration therein is much higher than that of the windward side. Also, a small clockwise vortex is obtained above the roof of the leeward building, and two small counterclockwise vortices are formed at both corners inside the canyon. The small vortex above the roof of the leeward building is caused by the severe separation when the free-stream collides at the up-left edge of the leeward building and is found in all canyons discussed in this paper (see Figs. 8 and 9). The small vortices on both corners of the in-canyon are formed by the action between the canyon walls and the large vortex. Contrary to the expectation, for the regular canyon ($H_b/W = 2$) (see Fig. 7b), there is no large vortex inside the canyon. For this case, the airflow streams start at a point (about $H/5$ above the ground) near the leeward wall and spread out into the canyon, the velocity of the airflow is low near the ground and windward wall, and it is slightly large at the upper half of the leeward wall. Thus, a small vortex with a core slightly lower than the building height and slightly biased toward the windward building is formed inside the canyon. Due to this small vortex, the pollutant concentration near the upper part of the windward wall is low, and the

Fig. 7 Airflow (streamlines and normalized velocity magnitude contours) and dimensionless $K$ pattern on the vertical central plane of the regular canyons; a $H_b/W = 1$; b $H_b/W = 2$
Fig. 8 Airflow and dimensionless pollutant concentration pattern on the vertical central plane of the canyons ($H/W = 1$) with different locations and heights of void deck; a leeward side & $H/W = 1/6$; b leeward side & $H/W = 1/4$; c windward side & $H/W = 1/6$; d windward side & $H/W = 1/4$; e both sides & $H/W = 1/6$; f both sides & $H/W = 1/4$
Fig. 8 (continued)
Fig. 9 Airflow and dimensionless pollutant concentration pattern on the vertical central plane of the canyons ($H_b/W = 2$) with different locations and heights of void deck; a leeward side & $H_v/W = 1/6$; b leeward side & $H_v/W = 1/4$; c windward side & $H_v/W = 1/6$; d windward side & $H_v/W = 1/4$; e both side & $H_v/W = 1/6$; f both side & $H_v/W = 1/4$
Fig. 9 (continued)
pollutant concentration at the rest part is very high. In particular, pollutants accumulate more on the windward wall by the airflow moving toward the windward side near the bottom of the canyon. Figures 8 and 9 depict the airflow and dimensionless pollutant distribution patterns on the vertical central plane inside the street canyons with the void deck. From Figs. 7, 8, and 9, three features are observed.

First, it can note that the void deck greatly changes the airflow field and pollutant distribution inside the canyon. As shown in Figs. 8 and 9, airflow and pollutant distribution patterns on the vertical central plane inside the canyons with void deck are quite different from that of the regular canyons. For example, for the canyon (\(H_f/W = 1\)) with void deck at the leeward building (see Figs. 8a and b), the strong airflow inflowing through the void deck of the leeward building moves toward the windward side, flows upward along the windward wall, and finally merges with the free-stream above the roof of the windward building. By this strong airflow, pollutants are removed out of the canyon and only slightly accumulate on the windward wall. Also, the large vortex of the regular canyon (see Fig. 7a) is completely disrupted inside the canyon; instead, two smaller counter-clockwise vortices are formed and two small vortices are generated at the corner and above the roof of the windward building. For the canyon with void deck at the windward building (see Fig. 8c and d), the airflow inflowing through the void deck of the windward building moves toward the windward side, flows upward along the windward wall, and finally merges with the free-stream above the roof of the windward building.

Second, as the void deck height increases, the pollutant concentration on the vertical central plane inside the canyons decreases. For the canyons (\(H_f/W = 1\)) with the void deck, comparing Fig. 8a and b, c and d, and e and f, it can be seen that even if the height of the void deck is increased from \(H_f/6\) to \(H_f/4\), the airflow field and pollutant pattern inside the canyon do not change significantly. However, the velocity and width of the basic airflow is increased, and the strength of the main vortex inside the canyon is weakened. Since the pollutants generated at the bottom of the street canyons are affected by this basic airflow, the pollutant distribution inside the canyon shows a tendency to slightly decrease as the height of the void deck increases. These features are the same ones even when the height of the building is \(2H\) (see Fig. 9a and b, c and d, e and f). The reason is that as the height of the void deck increases, the strength of the airflow flowing into the canyon through the void deck increases, and as a result, the strength of the basic flow inside the canyon becomes stronger. For example, comparing Fig. 9a and b, it can be noted that there is a basic airflow with a width almost equal to the height of the void deck inside the canyon, and the width of the basic airflow increases as the height of the void deck increases. As the width of the basic airflow increases, the main vortices are compressed that much, and as a result, the vortex strength becomes weaker. In particular, for the canyons with void decks at both sides (see Fig. 8e and f, Fig. 9e and f), the basic airflow strength is the strongest because the airflow passes directly through the canyon. Therefore, for these cases, a relatively large change of airflow speed is observed according to the increase in the void deck height, and the pollutant distribution is also observed very faintly.

Third, the building height increases have a positive effect on reducing the pollutant concentration of the vertical central plane. Comparing Figs. 8a and 9a, Figs. 8b and 9b, as the height of the building increases, among the two vortices existing inside the canyon, the vortex at the lower part is greatly developed in the direction of the building height, while the vortex at the upper part is greatly weakened. The reason is that the higher the building, the more the vortex at the lower part expands in the direction of the building height due to the basic airflow flowing upward along the windward wall. As this process deepens, the upper vortex becomes smaller by the free-stream passing through the canyon top and the vortex that develops below it. Also, the intensity of the basic airflow passing through the void deck and the canyon becomes much stronger. Therefore, as the height of the building increases, the pollutant distribution of inside the canyon is greatly reduced. The same is true for the canyon with void deck at the windward building (see Figs. 8c and 9c, Figs. 8d and 9d). For these cases, the concentration of pollutants inside the canyon is reduced more than other cases. For the canyons with the void deck at both buildings (see Figs. 8e and 9e, Figs. 8f and 9f), the vortex at the lower part is enlarged and the vortex at the upper part...
disappears due to the height of the building increases. As shown in Fig. 9e, the strength of the vortex inside the canyon is weak because a small share of the airflow inflowing into the void deck of the leeward building flows upward through the windward wall, and only a small share of it contributes to the formation of the vortex. Therefore, unlike Fig. 8e, a small vortex cannot be formed in the space between the free-stream passing through the canyon top and the vortex inside the canyon. In particular, for these cases, the strength of the basic airflow is the strongest since there are no obstacles to obstruct the airflow. By these basic airflows, traffic pollutants emitted from the canyon floor are almost completely removed from the canyon.

In summary, it can note that for the canyons with the void deck, the traffic pollutant diffusion is suppressed by the basic airflow that inflows from the void deck and passes through the pollutant generating region, and as a result, the void deck provides the advantageous environment for removing pollutants inside the canyon.

**Airflow and pollutant distributions at the pedestrian respiration level**

Figure 10 shows the airflow and pollutant distribution patterns at the pedestrian respiration level (1.5 m at the full scale) in the regular canyons without the void deck. For the regular canyon ($H_b/W = 1$) (Fig. 10a), outside the street canyon, two small vortices are formed on both sides of the leeward building and at the back of the windward building, respectively. Meanwhile, inside the canyon, the airflow that entered near the windward wall on both side of the canyon flows toward the center of the leeward wall. Therefore, the pollutant concentration is low near both sides and near the windward wall of the canyon, and high in the central part of the canyon and near the leeward wall. For the regular canyon ($H_b/W = 2$) (Fig. 10b), the small vortices mentioned above (existing for Fig. 10a case) are further developed larger outside the canyon. Inside the canyon, the airflow generated at two points near the windward wall on both sides of the canyon moves toward the center of the canyon and collides with each other, forming two symmetrical small vortices near the windward wall of the center of the canyon. Due to these airflow features, the pollutant concentration is low on both sides of the canyon, but a relatively wide high-pollutant region is formed in the center of the canyon. That is, when the height of the building increases, the pollutant concentration of the respiration plane near the windward wall becomes much higher. Figures 11 and 12 show the airflow and pollutant distribution patterns at the pedestrian respiration height for the canyons ($H_b/W = 1$ or 2) with void deck ($H_v/W = H/6$ and $H/4$). From Figs. 10, 11, and 12, it can be seen that for the canyons with and without void deck, the airflow structures and pollutant distribution patterns at the pedestrian respiration height are symmetrical about the vertical central line of the canyon. In addition, for a quantitative comparison, the mean pollutant concentration ($K$) values at the pedestrian respiration planes near both walls of fourteen canyons are given in Fig. 13 (see Fig. 1 for information on the pedestrian respiration planes). From the comparison analysis of Figs. 10, 11, 12, and 13, the effects of building height and the height and location of the void deck on the airflow and pollutant dispersion at the pedestrian respiration height are analyzed as follows.

First, the void deck has a significant effect on reducing the pollutant concentration at the pedestrian respiration planes inside the canyon. Comparing Fig. 10 with Figs. 11 and 12, it is found that for the canyons with the void deck, the pollutant concentration patterns at the pedestrian respiration height have completely new shapes, which is different to that in the regular canyons without the void deck. For example, for the canyon ($H_b/W = 1$) with the void deck ($H_v/W = 1/6$), when the void deck is at the leeward building (Fig. 11a),
the pollutant pattern near the leeward wall is not observed. However, near the windward wall, the pollutants are distributed parallel with almost the same width along the windward wall. This is explained by the fact that unlike in the regular canyon \((H_b/W = 1)\), the basic airflow passing through the void deck of the leeward building moves the pollutants generated from the line sources toward to the windward wall at almost the same speed in parallel. Therefore, for this case, many pollutants are accumulated on the respiration plane near the windward wall. In Fig. 13, comparing with the case of the regular canyon \((K_A = 40.4, K_B = 10.6)\), the mean \(K\) at the respiration plane near the leeward building is zero.

Fig. 11 Airflow and pollutant concentration distribution at the pedestrian respiration height of the canyons \((H_b/W = 1)\) with different locations and heights of void deck; a leeward side & \(H_v/W = 1/6\); b leeward side & \(H_v/W = 1/4\); c windward side & \(H_v/W = 1/6\); d windward side & \(H_v/W = 1/4\); e both side & \(H_v/W = 1/6\); f both side & \(H_v/W = 1/4\)
(\(K_A = 0\)) and that at the respiration plane near the windward building is much higher (\(K_B = 24.0\)). When the void deck is at the windward building (Fig. 11c), pollutants move towards the leeward wall by the airflow entering through the windward void deck. Also, two small vortices generate near the leeward wall by the airflow entering through the windward void deck and airflow entering to the canyon directly through both sides of the canyon. As a result, many pollutants accumulate at the respiration plane (\(K_A = 42.3\)), and tiny at the respiration plane (\(K_B = 2.8\)). The pollutant distribution near the leeward wall is almost parallel to the leeward wall in the central part and slightly protrudes where

Fig. 12 Airflow and pollutant concentration distribution at the pedestrian respiration height of the canyons (\(H_b/W = 2\)) with different locations and heights of void deck; a leeward side & \(H_v/W = 1/6\); b leeward side & \(H_v/W = 1/4\); c windward side & \(H_v/W = 1/6\); d windward side & \(H_v/W = 1/4\); e both side & \(H_v/W = 1/6\); f both side & \(H_v/W = 1/4\)
two small vortices exist. Also, the pollutant concentration in the two small vortex regions is slightly higher than that in the middle region and is the lowest on both sides of the canyon. When the void deck is at both buildings (Fig. 11e), due to the bottom of the canyon being opened by the two void decks, the strong airflow passes through the canyon unaffected by any obstacle; meanwhile, the pollutants are removed out of the canyon by this airflow. Therefore, the pollutant distribution on the pedestrian respiration planes near the leeward and windward building is hardly observed or significantly low ($K_A = 0$, $K_B = 8.4$).

Second, the increase of the void deck height has a distinct effect on the pollutant distribution at the pedestrian respiration height of the canyon. When the void deck is at the leeward building ($H_{v}/W = 1$) (Fig. 11a and b), observing the airflow distribution at the respiration height, the velocity of the basic airflow passing through the void deck of the leeward building slightly increases as the void deck height increases. Therefore, when void deck height is $H/4$, more pollutants are removed out of the canyon by the stronger basic airflow (Fig. 8b) that inflows through the void deck and passes the canyon floor and flows upward along the windward wall. As a result, less pollutant distribution ($K_A = 0$, $K_B = 19.5$) is observed at the respiration plane than when the void deck height is $H/6$. When the void deck is at the windward building ($H_{v}/W = 1$) (Fig. 11c and d), the increase of the void deck height leads to the increase of the airflow streamline density inflowing through the void deck of the windward building (the airflow streamline density indicates the strength of airflow). Due to this strengthened airflow, when the void deck height is $H/4$, the mean pollutant concentration ($K_A = 37.7$) of the respiration

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**Fig. 13** Mean dimensionless pollutant concentrations at the pedestrian respiration planes of the fourteen different street configurations; a leeward respiration plane ($K_A$); b windward respiration plane ($K_B$).

![Graph](image.png)
plane near the leeward wall is slightly decreased compared to that with the void deck height $H/6$, and that ($K_B = 3.3$) of the respiration plane near the windward wall is slightly increased. When the void deck is at both buildings ($H_b/W = 1$) (Fig. 11e and f), the velocity of the basic airflow passing through the canyon floor increases significantly as the void deck height increases, and by this airflow, pollutants are almost completely removed out of the canyon. Therefore, in Fig. 11e, there are two small and low pollutant concentration distribution patterns at both ends of the leeward building, and in Fig. 11f, no pollutant distribution pattern is observed at all ($K_A = 0$, $K_B = 6.6$). Also, as shown in Fig. 12, for the canyons ($H_b/W = 2$) with the void deck, as the void deck height increases, the velocity of the airflow flowing into the canyon through the void deck slightly increases. Because of this, as in the case of the canyons ($H_b/W = 1$) with the void deck (Fig. 11), the pollutant concentrations at the respiration planes are reduced. However, the pollutant pattern change is quite small. To be concrete, according to the quantitative analysis of the mean $K$ at the pedestrian respiration planes (Fig. 13), when the void deck is at the leeward building (Fig. 12a and b), the mean pollutant concentration ($K_B = 13.9$) is slightly reduced compared to the case that the void deck height is $H/6$ ($K_B = 18$). When the void deck is at the windward building (Fig. 12c and d), the mean $K$ at the respiration plane near the leeward wall decreases from 36.4 to 31.1. When the void deck is at both buildings (Figs. 12e and f), the mean $K$ at the respiration plane near the windward wall decreases from 7.5 to 6.9. This means that when the building height is higher, the variation of the void deck height has minor effect on the mean pollutant concentration.

Third, from the comparison between Figs. 11 and 12, it can be seen that for the canyons with the void deck, the higher the building height, the lower the pollutant concentration at the respiration level, unlike in the regular canyon. This is because the velocity of the basic airflow flowing into the canyon through the void deck increases significantly as the building height increases. For example, when the void deck ($H_v/W = 1/4$) is at the leeward building, comparing Figs. 11b and 12b, for the canyon with building height $2H$, lower pollutant distribution pattern is observed at the respiration level due to the velocity of the airflow inflowing through the void deck of the leeward building is much faster than that for the canyon with building height $H$. For this case, the mean $K$ of the respiration plane near the windward wall decreases from 19.5 to 13.9 as the building height increases. When the void deck ($H_v/W = 1/4$) is at the windward building (Figs. 11d and 12d), as the building height increases, the velocity of the airflow inflowing through the void deck of the windward building increases, and eventually, the pollutants are more compressed toward to the leeward wall. For this case, the mean $K$ of the respiration plane near the leeward wall reduces from 37.7 to 31.1, and the mean $K$ of the respiration plane near the windward wall decreases from 3.3 to almost 0. When the void deck ($H_v/W = 1/4$) is at both buildings (Figs. 11f and 12f), there are no pollutant patterns in the street canyon due to the pollutants being removed out of the canyon through the void deck of the windward building by the basic airflow passing through the void decks on both sides of the canyon. From Fig. 13, when the building height is $H$ or $2H$, the mean $K$ of the respiration planes near the windward wall is very low as 6.6 and 6.9, respectively.

Fig. 14 Dimensionless pollutant concentration patterns on the leeward wall (A) and windward wall (B) of the regular street canyons; a $H_b/W = 1$; b $H_b/W = 2$.
From the above analysis, it can be found that increasing the height of the void deck and building can significantly lower the pollutant concentration at the pedestrian respiration height of the street canyon and can provide a very good environment for pedestrian health.

**Pollutant distributions on the canyon walls**

The pollutant concentration distribution on both walls of the canyon is closely related to the health of indoor residents. Therefore, in this section, we evaluate the pollutant concentration levels on both walls of the canyon with the void deck. Figure 14 depicts the pollutant distribution on both walls of the regular canyons ($H_v/W = 1$ or 2) without the void deck. For the regular canyon ($H_v/W = 1$) (Fig. 14a), the pollutant pattern on both walls like a “saddle” shape, and symmetrical distributions along the vertical central line, and the pollutant concentration of the central part is higher than that of the sides. The pollutant concentration of the leeward wall is much higher than that of the windward wall. This is because fresh airflow inflowing from both sides of the canyon flows toward the leeward wall by the large vortex (see Figs. 7a and 10a) formed in the center part of the canyon and moves pollutants to the center of the leeward wall. For the regular canyon ($H_v/W = 2$) (Fig. 14b), pollutant patterns on...
both walls have symmetrical distribution in the shape of a “mushroom cap.” The pollutant concentration in the middle part of the leeward wall is slightly higher than that of the regular canyon ($H_b/W = 1$). However, many pollutants are accumulated on the windward wall by the airflow (see Figs. 10b and 7b) flowing from the leeward wall to the windward wall inside the canyon, so the high-pollutant region is formed in the middle part of the windward wall. Figures 15 and 16 show the pollutant distribution patterns on both walls for the street canyons with the void deck, with building height of $H$ and $2H$, respectively. In Fig. 17, the mean dimensionless $K$ values on both sides of the street canyons with and without void deck are quantitatively compared. From Figs. 14, 15, 16, and 17, comparing the pollutant distribution on both walls of canyons with and without void deck, we can find several features.

First, the mean $K$ on the wall of the buildings with the void deck inside the canyon is very low, almost equal to zero. At walls with void deck in Figs. 15 and 16, the pollutant distribution patterns are not observed. The reason is that the pollutants generated from the canyon floor are directly removed out of the canyon by the basic airflow, as shown in Figs. 8 and 9. However, various pollutant distribution patterns appear on the walls without the void deck. For example, for the canyons with the void deck at the leeward building, the pollutant

![Image](image_url)

**Fig. 16** Dimensionless pollutant concentration patterns on the leeward wall (A) and windward wall (B) of the canyons ($H_b/W = 2$) with different locations and heights of void deck; a leeward side & $H_b/W = 1/6$; b leeward side & $H_b/W = 1/4$; c windward side & $H_b/W = 1/6$; d windward side & $H_b/W = 1/4$; e both side & $H_b/W = 1/6$; f both side & $H_b/W = 1/4$.
contour lines are distributed almost horizontally along the canyon (see Fig. 15a and b, Fig. 16a and b). This is because the airflow inflowing through the void deck of the leeward building moves the pollutants to the windward wall with almost the same strength (see Fig. 11a and b, Fig. 12a and b). In particular, for these cases, unlike regular canyons without void deck (Fig. 10), since there is no airflow inflowing from both sides of the canyon (see Table 4, for the canyons with the void deck at the leeward wall, $\Delta CH_{side1}$ and $\Delta CH_{side2}$ are almost zero), and the pollutants do not collect in the middle of the canyon and are evenly distributed horizontally on the windward wall. For the canyons with the void deck at the windward building, pollutant patterns on the leeward wall resemble a “horn” and form a symmetrical distribution (see Fig. 15c and d and 16c and d). While the basic airflow inflowing through the void deck of the windward building reaches the leeward wall and then flows toward both sides of the canyon, it loses kinetic energy as a result of the action with the other airflow inflowing from both sides of the canyon (see Fig. 11c and d and 12c and d). Therefore, the airflow velocity is reduced in this active region, pollutants are accumulated, and finally, pollutant distribution patterns similar to “horn” are formed on the leeward wall. For the canyons with the void deck on both buildings, pollutants are removed out of the canyon by the strong basic airflow passing through the bottom of the canyon (see Fig. 8e and f and 9e and f), so the pollutant distribution is not observed on both walls (Fig. 15e and f and 16e and f).

Second, increasing the void deck height reduces the pollutant concentration of the canyon walls. For the canyons with the void deck, from the comparison of Figs. 15 and 16, it can be seen that the pollutant concentration on the walls without the void deck decreases when the void deck increases from $H/6$ to $H/4$. This is because as the void deck height increases, the velocity of the basic airflow passing through the void deck the canyon is increased (see Figs. 8 and 9). As a result, more pollutants are moved out of the canyon by this strong airflow. Especially, for the canyons with the void deck at both buildings, the pollutant distribution patterns on the canyon walls are not observed (Figs. 15 and f and 16e and f). This shows that for the canyons with the void deck at both buildings, void deck height of $H/6$ (3 m at a full scale) is sufficient to remove pollutants on both walls.

Third, for the canyons with the void deck, the pollutant concentration on both walls of the canyon decreases as the building height increases. For the regular canyons, it can be seen that as the building height increases, the mean $K$ on the leeward wall reduces from 26.0 to 18.3 and the mean $K$ on the windward wall increases from 6.9 to 22.0 (see Fig. 17). However, for the canyons with the void deck, the mean $K$ on both walls reduces when the building height increases from $H$ to $2H$. From Figs. 15 and 16, for the canyons with void deck of the same height and location, the strength of the basic airflow passing through the void deck is much stronger for the canyons ($H_b/W = 2$) than for the canyons ($H_b/W = 1$). The stronger the airflow, the more pollutants are released out of the canyon. From this, we can find that for the canyons with the void deck, the higher the void deck and the building height, the lower the pollutant concentration on both walls of the canyon. Especially when the void deck is at both buildings, the mean concentration on the canyon walls is extremely low, so it could provide a very good living environment for the near-road residents compared to the regular canyon.

Conclusions

In this paper, we explored the effects of void deck on the airflow and pollutant diffusion characteristics inside the street canyon. In 3D street canyon, numerical simulation validated by WT data, different building heights, various locations, and heights of the void deck is considered. From the analysis of the CFD numerical simulation results, the following conclusions are reported.

The void deck location has a significant effect on the airflow and pollutant distribution inside the street canyon. Unlike the regular canyons, for the canyons with the void deck, pollutants are removed out of the canyon by the strong fresh airflow inflowing to the canyon through the void deck. Therefore, for the canyons with the void deck, the $ACH$ is significantly increased and $ACH'$ (the perturbation change of turbulence) is reduced compared to the regular canyons. When the void deck is at both buildings, the strong airflow passes directly through the bottom of the canyon, so the $ACH$ is the highest (167.6–230.3%), followed by the case where the void deck is at the leeward building (153.1–205.2%). When the void deck is at the windward building, due to the reverse airflow inflows to the canyon through the void deck of the windward building, the strength of airflow is the weakest and as a result the $ACH$ is the smallest (107.8–119.0%). The highest $NEV^*$ is obtained in the canyon with void deck at both building, which is 38.3 times, 13 times, and 6.4 times of that in the regular canyons, the canyon with leeward void deck, and the canyon with windward void deck, respectively. Here, because a weak airflow enters the canyon with the windward void deck, the smallest $NEV^*$ is observed therein.

As the void deck height increases, the strength of airflow inflowing to the canyon through the void deck becomes stronger. This airflow characteristic allows more pollutants to be removed out of the canyons for the canyons with higher void deck height. Therefore, $ACH$ increases as the void deck height increases. In particular, the effect of void deck height
is the greatest when the void deck is located at both buildings and is the smallest when the void deck is located at the windward building. At the same building height, increasing the void deck height significantly increases $NEV^\star$. Compared to regular canyon, for the windward void deck, increasing the void deck height from $H_b/W = 1/6$ to $1/4$ increases the canyon’s $NEV^\star$ slightly (110%). However, for the leeward and both void decks, $NEV^\star$ significantly increases to 130% and 160%, respectively. In addition, the pollutant concentration at both walls of the canyon and at the pedestrian respiration height also decreases as the void deck height increases. Since pollutants are moved by the strong airflow flowing into the canyon through the void deck, the mean pollutant concentration on the wall of the building with the void deck and on the pedestrian respiration plane close to it is near zero. The mean pollutant concentration on the wall of the building without the void deck and on the pedestrian respiration plane close to it is lower than that of the regular canyon except for one case (for the canyon ($H_b/W = 1$) with the void deck at the leeward building). That is, as the void deck height increases, a very good environment for the health of pedestrians and near-road residents inside the street canyon can be provided. For the canyon with the void deck at both buildings, void deck height of $H_b/6$ (3 m at a full scale) is sufficient.

For the canyons with the void deck, building height has a significant influence on the intensification of pollutant diffusion inside the canyon. As the building height increases, $NEV^\star$ increases by 280–360% for the canyons with the windward void deck and 210–220% for the canyons with the leeward and both void decks compared to regular canyons. Therefore, for the canyons with the void deck, when the building height increases, the strength of airflow inflowing to the canyon through the void deck increases, and more pollutants are removed out of the canyon. In addition, the pollution concentration at both walls of the canyon and at the pedestrian respiration height also decreases with increasing building height, which has the same tendency as when the void deck height increases. However, the increase in the building height has a more pronounced effect than the increase in the void deck height. That is, the void deck is very advantageous in reducing the risks of pollutant of the pedestrians and residents inside the street canyons composed of high-rise buildings.

From the above conclusions, we can find that the void deck is a very effective architectural feature for improving traffic pollution in urban canyons in the tropics. In the future, the void deck can be used very effectively to reduce the damage to pedestrians and residents caused by traffic pollutants in a street canyon consisting of high-rise buildings.

Yang Luo has mainly contributed to guide the establishment of numerical models and the paper revision.

Kwang Song Jon has contributed to the processing of the numerical results and drawn the figures and tables.

Peng-Yi Cui has contributed to the processing of the numerical results and drawn the figures and tables.

Yuan-dong Huang as the corresponding author and supervision, has carefully edited the grammar, spelling, sentence structures of this paper.

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