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The Numerical Simulation of Uplifted Street Canyon on Flow Field Structure and Pollutant Diffusion

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Abstract: The flow field structure, pollutant concentration distribution and dimensionless concentration evolution of uplifted street canyon has been analyzed in this study. Different from the ideal street canyon, the pollutant concentration distribution of the uplifting street canyon is higher at the bottom, lower at the top, higher at the windward side and lower at the leeward side. The total pollutant concentration (TPC) generally decreases with the increase of leeward building lifting height while the lift height increases with the same total building height or the total building height increases with increase in the lifting height. It is beneficial to the pollutant emission of in street canyon. On the contrary, the TPC increases when the total building height increases with the same lift height. The main reason is that the vertical length of the vortex increases, which is more difficult for pollutants to be discharged from the street canyon.

Keywords: Street canyon, Uplifted building, Flow field structure, Pollutant diffusion

Nomenclature

W	The width of street canyon(m)
H_b	The height of the main structure of the building (m)
H_{vd}	Lifting height of leeward side buildings (m)
H_{eff}	The sum of H_b and H_{vd} (m)
U	inlet velocity (m/s)
tke	turbulence
U_*	Friction speed(m/s)
Z	Vertical distance from the ground (m)

Z_0	Surface roughness height (m)
C_μ	constant
Q	Pollution source release rate
C_α	Volume fraction of pollution source.
<i>Greek symbols</i>	
$\mathcal{E}$	Dissipation of turbulent energy per unit mass
κ	Karman constant (= 0.41)

37

38 **1 Introduction**

39 The street canyon with buildings on both sides of streets will cause automobile
40 exhaust to accumulate and difficult to spread (Prakash et al. 2019). The existence of
41 these pollutants brings a great threat to human health (Paul et al. 1992; Sabatino et al.
42 2013; Blocken 2015; Robert et al. 1996). Therefore, the influence of building structure
43 on the pollutant diffusion and distribution in the street canyon has been paid more and
44 more attention in decades (Grimmond et al. 1999; Hang et al. 2012; Jian et al. 2013;
45 Buccolieri et al. 2015; Murena et al. 2014; Ramponi et al. 2015).

46 In urban canyons, some buildings are often raised and their lower parts were used
47 as parking lots for vehicles, which enhances the airflow at the bottom of street canyon
48 (Niu et al. 2015). It has been found that the porosity of building at the bottom can
49 enhance the ventilation of pedestrian horizontal canyons, but the porosity of the upper
50 part would not (Yuan et al. 2012). And it has been confirmed that the horizontal wind
51 speed of pedestrians would be influenced much more seriously with building uplift than

the normal building at the central area. When the buildings in the central area rise to be the highest one, the horizontal wind speed of pedestrian-level reached the highest speed (Tse et al. 2017). Chew et al. (2018) used both experimental and numerical methods to investigate pedestrian-level wind speed enhancement with void decks in urban street canyons. The results showed that the enhanced wind speed was beneficial for pollutant dispersion in tropical cities. They also extended the street canyon to three dimensions in subsequent work, which proved that the uplift building increased the horizontal wind speed of pedestrians significantly. A series of studies have described the elevation of buildings height will significantly affect pedestrian wind speed and air flow field in street canyons (Chew et al. 2019).

Martin et al. (2005) studied the flow characteristics in 2D asymmetric ascending street canyons, they found that the vortex number in ascending street canyons was a function of the ratio of buildings height to width. Soulhac et al. (2001) studied pollutant diffusion in 2D ascending street canyons according wind tunnel experiments, they found that the peak concentrations in square and stepped street canyons were similar near the windward surface. Ohba (1998) and Addepalli (2015) found that the flow field structure of street canyons was mainly affected by leeward side buildings. These studies showed that the flow state in the street canyon was the interaction result of the windward and leeward buildings.

It has been analyzed the influence of four different shapes of buildings (with or without lifting design) on pedestrian horizontal wind speed. Results showed that the lift-up design can improve the wind comfort in building surroundings (Du et al. 2017).

Xie et al. (2005) built different turbulence models to simulate pollutant diffusion in street canyons. They found that the characteristics of pollutant dispersion was influenced by configuration of vortex. The functions were different when different kinds of street configurations were selected. It has been studied the effects of building height, aspect ratio and roof shape on the distribution of CO₂ clouds by wind tunnel experiment and CFD simulation. The results showed that vertical recirculation would be enhanced by increasing windward-side building height (Tan et al. 2018).

Building structures have attracted a lot of attention on street canyon pollutant discharge. However, the specific process influenced by the lifting height of buildings has not been clearly explored, and few studies about the uplifted street canyons has been reported. In this study, different kinds of uplifted street canyons have been considered to investigated the flow field structure and pollutant concentration distribution.

2. Model establishment

2.1 Physical model establishment and numerical setting

The two-dimensional street canyon model is established at 1/200 of the actual street canyon size as shown in Fig. 1. The height and width of the building on the windward side are both 0.12 m and the building on the leeward side raised as shown in Fig. 2. The building height is divided into two parts, where H_b represents the main building height and H_{vd} represents the leeward side building height, and H_{eff} represents sum of H_b and H_{vd} . All height considered in this study are listed in Table 1. The pollution source is 0.008 m long, simulating a motor vehicle lane. Both the two

sides of pollution source are 0.002m wide, which is regarded as sidewalks. Wind speed condition is set to be 3m/s.

Fig. 1 Two-dimensional street canyon model

Fig. 2 Two-dimensional street canyon model parameters

Table 1 Numerical simulation case parameter table (a) The total height does not change and the lifting height changes (b) The total height changes and the lifting height changes (c) The total height changes and the building height changes

(a)

Case	H _b (m)	H _{vd} (m)	H _{eff} (m)	W(m)	No. canyon
1	0.12	0	0.12	0.12	1

2	0.115	0.005	0.12	0.12	1
3	0.11	0.01	0.12	0.12	1
4	0.105	0.015	0.12	0.12	1
5	0.1	0.02	0.12	0.12	1

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107 (b)

Case	H _b (m)	H _{vd} (m)	H _{eff} (m)	W(m)	No. canyon
1	0.12	0	0.12	0.12	1
2	0.12	0.005	0.125	0.12	1
3	0.12	0.01	0.13	0.12	1
4	0.12	0.015	0.135	0.12	1
5	0.12	0.02	0.14	0.12	1

108

109 (c)

Case	H _b (m)	H _{vd} (m)	H _{eff} (m)	W(m)	No. canyon
1	0.12	0.01	0.13	0.12	1
2	0.14	0.01	0.15	0.12	1
3	0.16	0.01	0.17	0.12	1
4	0.18	0.01	0.19	0.12	1
5	0.20	0.01	0.21	0.12	1
6	0.22	0.01	0.23	0.12	1

110

2.2 Calculation model and boundary conditions

In this study, standard $k-\varepsilon$ model was used for the 2D street canyons. The boundary conditions of the model were as follows:

The top of the calculation domain was a symmetric boundary condition (both the normal velocity and the flow velocity gradient are zero). No-slip wall boundary was set for all surfaces corresponding to the ground and the buildings (Zhang et al. 2021). Outflow boundary conditions were selected by calculating the domain exit. The atmospheric boundary conditions were chosen for the velocity inlet of calculation domain (Rollet-Miet et al. 1999), and the input velocities of atmospheric boundary condition were realized by UDF programming. The inlet velocity was U , the turbulent kinetic energy was tke , and the turbulent dissipation rate was ε . The calculation formula was as follows:

$$U = \frac{U^*}{\kappa} \ln \left(\frac{z + z_0}{z_0} \right) \quad (1)$$

$$tke = \frac{U^{*2}}{\sqrt{C_\mu}} \quad (2)$$

$$\varepsilon = \frac{U^{*3}}{\kappa(z + z_0)} \quad (3)$$

where U^* is the friction velocity given in formula Eq.(4), κ is the Karman Constant (0.41), z is the vertical distance to the ground, and z_0 is the surface roughness height, C_μ is the constant (0.09).

$$U^* = \kappa \frac{U(z = z_{ref})}{\ln\left(\frac{z_{ref} + z_0}{z_0}\right)} \quad (4)$$

Eq. (1) and Eq. (4) can be simplified as Eq. (5) dimensionless velocity curves:

$$\frac{U}{U(z = z_{ref})} = \frac{\ln\left(\frac{z + z_0}{z_0}\right)}{\ln\left(\frac{z_{ref} + z_0}{z_0}\right)} \quad (5)$$

In order to explain the pollutant distribution more clearly in the street canyon and its relationship with the building structure parameters, the dimensionless method of pollutant concentration in the street canyon has been described, and the formula is shown as follow:

$$K = \frac{\int C_\alpha dV}{Q} \quad (6)$$

where Q is the pollution source release rate of 0.0001 kg/s. κ is the Karman Constant (=0.41). C_α is the volume fraction of pollution source. V is the volume of pollution source.

2.3 Validation of the model

This study uses the experimental from the US Environmental Protection Agency Fluid Modeling Facility were measured in an open return wind tunnel and chosen for validation of the RNG k- ϵ turbulence model and grid independence (Lien et al. 2004). As shown in Fig. 3, it is a schematic diagram of a two-dimensional building array for the wind tunnel experiments. As shown in Fig. 4, the numerical simulation results of the reference case are in good agreement with the experimental results, which indicates that the selection model calculation parameters are correct (Chew et al. 2018).

Fig. 3 Numerical verification model and grid division (Lien et al. 2004)

(a)

(b)

(c)

Fig.4 Reference case of standardized mid-line velocity profile in Canyon Four (Chew et al. 2018) (a) Mean stream-wise velocity (b) Mean vertical velocity (c) Turbulence kinetic energy

3. Analysis of flow field structure and pollutant diffusion

3.1 The lift height increases while the total height remains a constant

Fig. 5 shows the flow field structure and pollutant diffusion diagram when the lift height increases while the total height remains a constant. For $H_{vd} = 0$ m, a main clockwise vortex is formed inside the street canyon and the vortex center is deviated the upper windward corner of street canyon. This is consistent with previous research (Ding et al. 2019). For a single vortex structure, the main clockwise vortex brings the pollutants to leeward side of street canyon. The flow field structure in the street canyon changes from a single vortex to a tri-vortex structure with the H_{vd} increases. At this time, the direction of the main vortex in the canyon reversed completely and turned into a counterclockwise vortex. The air flow velocity begins to increase, which indicates that the ventilation capacity in the canyon is enhanced. The pollutant is mainly concentrated on the windward side and overflowing outside the street canyon. It can be seen that the distribution of pollutants will be influenced by the uplift of leeward side buildings seriously.

$$H_{vd} = 0\text{m}$$

$$H_{vd} = 0.005\text{m}$$

$$H_{vd} = 0.01\text{m}$$

$$H_{vd} = 0.015\text{m}$$

$$H_{vd} = 0.02\text{m}$$

Fig. 5 The lift height increases while the total height remains a constant

3.2 The total height increases with increase in the lifting height

Fig. 6 shows the flow field structure and pollutant diffusion diagram when the total height increases with the increase in the lifting height. As H_{vd} increases, the total height increases with the increase in the lifting height. As H_{vd} increases, the speed of the airflow in the canyon increases sharply. For $H_{vd} = 0.005\text{m}$ and $H_{vd} = 0.01\text{m}$, the flow field structure changes most obviously with the increase in wind speed. The number of vortices in the street canyon gradually increase from 1 to 3. For $H_{vd} > 0.015\text{m}$, the number and the relative position of vortex is fixed, and both the vortex size and rotation direction are basically the same. The air flow structure in the street canyon reaches a stable state. Then, the vortex changes little and the pollutant will flow out from the street canyon along the windward building.

$$H_{vd} = 0m$$

$$H_{vd} = 0.005m$$

$$H_{vd} = 0.01m$$

$$H_{vd} = 0.015\text{m}$$

$$H_{vd} = 0.02\text{m}$$

Fig. 6 The total height increases with increase in the lifting height

3.3 The building height increases with the same lift height

Fig. 7 shows that flow field streamline and pollutant diffusion diagram when the building height increases with the same lift height. For $H_b = 0.12\text{m}$, there are three vortices in the street canyon, and the pollutant concentration distribution is high at the bottom and low at the top, while it is high near the windward side and low near the leeward side. For $H_b > 0.14\text{m}$, the stable structure of two vortices is maintained in the street canyon with the increase in the lifting height. A large counterclockwise vortex on

the leeward side and a small clockwise vortex in the lower right corner, the size of large vortex on the leeward side increases in the vertical direction, leading to the gradual expansion of the pollutant diffusion range (Hong et al. 2000).

$$H_b = 0.12 \text{ m}$$

$$H_b = 0.14 \text{ m}$$

$$H_b = 0.16 \text{ m}$$

$$H_b = 0.18 \text{ m}$$

$$H_b = 0.2 \text{ m}$$

$$H_b = 0.22 \text{ m}$$

Fig. 7 The building height increases with the same lift height

4. Dimensionless analysis of pollutant concentration

4.1 The lift height increases while the total height remains a constant

For assessing the air quality of a street canyons, the pollution level at pedestrian height (1.5 m above ground) must be investigated (Ng et al. 2014). As shown in Fig. 8, the dimensionless concentration of CO in the entire street canyon first increased and then decreased with the increase of H_{vd} . As ventilation increases within the canyon, pollutants overflow out of the street canyon, so the TPC decreases. For $H_{vd} > 0.015\text{m}$, the TPC decreases by more than half. These results suggest that the uplift of leeward side buildings is conducive to the pollutant discharge from the entire street canyon. The dimensionless concentration of CO in the pedestrian level on the leeward side decreased. The CO concentration decreases sharply with the increase of uplift at first, and then leveled off. On the contrary, the dimensionless pollution concentration in the pedestrian level on the windward side rises firstly and then decreases slightly, and the concentration was higher than the initial value. The dimensionless pollution

concentration of pedestrians on the windward side increased because of the uplift of buildings. This is related to the reversal of the flow field in the street canyon (Ding et al. 2019).

Fig. 8 The evolution of dimensionless concentration of CO in the street canyon with different lifting heights

4.2 The total height increases with increase in the lifting height

The TPC and pollutant concentrations at the pedestrian level are plotted in Fig. 9. Compared with the results without lift height, the dimensionless concentration of CO in the entire street canyon drops from 58 to 25 when $H_{vd} = 0.20\text{m}$. The dimensionless concentration of CO in the pedestrian level on the leeward side decreases with the increase in H_{vd} . The ones increase firstly and then decreases with the increase of H_{vd} on the windward side and the final value is larger than the initial value. It dedicates that the uplifting effect of the leeward side buildings aggravates the pollution concentrations in the pedestrian level on the windward side.

Fig. 9 The dimensionless concentration of CO in the street canyon changes with the lifting height

4.3 The building height increases with the same lift height

As shown in Fig. 10, it is shown that the TPC increases with the increase of the size of main vortex structure which is difference with the previous works. The vertical length of the vortex is proportional to the H_b , which makes the pollutions much more difficult to remove from the street canyon. Fig. 10 shows that the dimensionless concentration of CO is influenced by H_b a little in the pedestrian area on the leeward side. Similar to the leeward side, the dimensionless concentration of CO in the pedestrian level on the windward side changes slightly with the increase in H_b .

Fig. 10 The dimensionless concentration of CO in the street canyon changes with the height of the main structure of the building

5. Conclusion

In this study, CFD simulations are carried out on the flow field structure, pollutant concentration distribution and non-dimensional concentration changes of three uplifted street canyons. The effects of the lift height and building height were studied in detail.

1) The three uplifted street canyons eventually form a relatively stable flow field structure. A tri-vortex stable structure has been formed when the total height increases with increase in the lifting height. A tri-vortex stable structure has been formed when the lift height increases with the same total height. A double-vortex stable structure has been formed while the building height increases with the same lift height.

2) For the uplifted street canyons, the pollutant concentration distributions are high at the bottom and on the windward side, while the one is low at the top and on the leeward side.

3) The TPC of street canyons decreases by more than half when the lift height increases with the same total height. The same phenomenon will be observed when the total height increases with increase in the lifting height. The pollutant concentration much more difficult to remove from the street canyon when the height of windward building is higher than the one of leeward building under the same lift height.

Author contribution

Mengru Sun: investigation, methodology, data analysis, software, writing;

Yuqing Song: data curation, investigation, revise original draft.

Changfa Tao: investigation, methodology, data analysis, software, review and editing.

Xiaoping Liu: investigation, methodology, software.

Tao Wang: investigation, review and editing.

Qin Shi: supervision, review and editing.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval

Not applicable

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Conflict of interest

The authors declare no competing interests.

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