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Computer-Aided Simulation Analysis on the Impact of Various Opening Patterns in High-Rise Opening Building towards Pollutants Dispersion †

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Abstract: Taiwan is the fourth most urbanized country in Asia, where the urban spatial structure of high-rise and density hinders urban ventilation. Studies have proven that opening buildings reduce the area of windward surfaces, which can effectively mitigate the urban heat island effect and disperse pollutant accumulation. Until now, most researchers have discussed the differences in heights and sizes of openings in the opening buildings, but few discussed the influence of opening patterns on urban ventilation. Thus, we set the building unit to 30 × 30 m with 160-m height with the opening height as tall as 0.45 times the building height and a 9% opening rate, distributed in 6 × 6 ideal city configuration Four cases (case A: no opening, case B: middle square, case C: right square, and case D: middle rectangular) with different arrays of opening buildings were compared with ANSYS Fluent v18 to simulate the wind environment and NO_2 pollutants. The results showed that the opening building improved the permeability of street ventilation and air circulation, which greatly increased the wind speed at a height of 72 m. The distribution of pollutants was affected by the distance from the pollution source and the width of the street. Pollutants were gradually dispersed as the height increased. Case D of a long-narrow rectangular opening (adjacent to the pedestrian floor) and the venture effects formed eddy currents above and below the opening, which effectively improved the ventilation in the street canyon. Therefore, it had the best wind speed on the pedestrian level among the cases. The wind speed of the 72 m-high floor was much higher than that of case A, and the vortex generated by the airflow flowing through the opening in the street canyon increased the diffusion effect of pollutants. Overall, the opening building with a rectangular opening was the optimum solution in terms of wind speed improvement and pollutant removal. In addition to the opening design in the building facade, it is recommended to provide sufficient open space to improve air circulation in the building block and disperse pollutants.

Keywords: high-rise opening building; urban street canyon; traffic pollutant (NO_2); CFD analysis

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1. Introduction

Major cities are gradually developing into compact cities to respond to urbanization, increase population carrying capacity, and maximize land use. High-density development in compact cities challenges urban growth, planning, and design. For example, the wall effect formed by high-rise buildings easily hinders urban ventilation and makes it difficult to discharge pollutants. Long-term exposure to pollutants can be harmful to health. Nitrogen dioxide can easily cause diseases such as macular degeneration, diabetes, asthma, and fetal heart disease, and its concentration is positively correlated with the incidence of COVID-19 [1]. Therefore, we explore the impact of NO_2 on the urban environment.

Ventilation problems and pollutant accumulation are the inevitable results of high-density living and urbanization in developing countries [2]. High-rise buildings block wind flow, and areas with no wind and weak wind are prone to heat and pollutant accumulation. Therefore, the wind corridor design has been implemented in many countries recently. However, it is not easy to re-plan the urban air corridors in densely built cities, so the opening buildings conducive to urban ventilation have gradually received attention [3]. In the past, the research on opening buildings mainly focused on the structure of building mass and the reduction of wind resistance [4–6]. The related research still focuses on the simulation of the opening building's opening rate, height, and street aspect ratio [3,7,8]. There is a lack of relevant research on the impact of different opening types of opening buildings on urban microclimates.

In this study, ANSYS Fluent v18 was used to simulate the wind environment and pollutants and to discuss the influence of four openings on the diffusion of NO_2 pollutants in street canyons. We referred to the ideal city 6 × 6 configuration of Li et al. [9], and the building units were set to be 30 × 30 × 160 m. The research is carried out as follows:

(1) Comparing the wind speed distribution at the pedestrian floor (1.5 m) and the upper floor (72 m) of the four buildings with different openings

(2) The pollutant diffusion distribution of four different opening types of high-rise buildings at different heights (1.5, 30, and 61.5 m) was compared.

2. Literature Review

2.1. Relationship between Cities of Different Densities and Urban Wind Environment

Due to the limited land resources in urban areas, the buildings gradually become high-rise and high-density. High-rise buildings hinder urban ventilation, quickly generate strong winds, or affect air circulation. Strong winds have an impact on pedestrian wind fields and safety [10], and areas with no wind and weak wind are prone to heat accumulation and pollutant accumulation. This affects the pedestrian wind field. For compact urban areas, urban design planning can effectively enhance urban wind energy potentials changing urban wind conditions by adjusting urban density, street width, building geometry, and layout can affect [11]. The joint research report of the Institute of Architecture of the Ministry of the Interior [12] pointed out that the air corridor can effectively use the wind's ability to regulate heat to cool down the urban high temperature, improve the quality of the living environment, and reduce the accumulation of harmful pollutants. Owing to the importance of wind corridor construction, many countries have successfully implemented urban ventilation corridors such as Vauban, an ecological community in Freiburg, Germany, the draft axis planned for Tokyo Bay, and the construction of five urban ventilation corridors in Munich, Germany. According to the research, the wall effect formed as a result of high-rise buildings affects the urban wind environment. At the same time, trees and objects cause secondary interference [13]. Tsai [14] selected street profile samples in Kaohsiung's city center and pointed out that the composition of the urban wind field is closely related to the street profile form.

The increase and decrease in wind speed have different effects. However, the building height has the most significant impact on improving the road ventilation effect which creates the urban heat island effect and the impact on ventilation efficiency. Research by the Institute of Architecture of the Ministry of the Interior [15] pointed out that high-rise buildings create obstacles to the wind field, which changes the state and speed of the airflow around the building, forms a massive obstacle to the airflow, and results in an undercut, shrinkage, channelization, vortex, and angle. Flow, wake, shading, and cross-window effects of the strong wind generated by this effect affect the safety and comfort of pedestrians. Lin [16] studied the effects of different building heights, building densities, and ambient wind directions on the urban canopy (UCL) ventilation and used the removal flow rate (PFR) and air exchange rate (ACH) to evaluate the building. The height change increases the airflow around high-rise buildings but reduces the ventilation effect near low-rise buildings. Mei et al. [17] proposed that lower building density can improve ventilation efficiency. Better ventilation performance can be obtained in compact urban development by reducing frontal area density or building number. Luis [18] analyzed the influence of different urban types on the thermal effect. He pointed out that when the building group coverage rate is 30−40%, the city's environmental impact and external trade-offs can be well balanced.

2.2. Impact of Air Pollutants in Urban Areas on Wind Environment

Various types of waste discharge make the amount, concentration, and duration of smoke and harmful gases in the atmosphere reach a certain level and cause a significant burden on the environment, known as air pollution [19,20]. The main factors affecting the diffusion of pollutant $PM_{2.5}$ in cities are microclimate, including temperature, wind speed, wind direction, and air pressure [21]. The frequent industrial and commercial activities and the development of high-rise and high-density buildings caused by the urban high population density change the city's original environmental wind field. Studies have pointed out that improving air quality is not only to suppress the emission of pollution sources but also to effectively improve the urban ventilation environment through urban planning and architectural design—influence [3,7,16]. The ventilation effect also becomes different under the urban development patterns of different densities (street pattern, building height, and building density). If the street pattern becomes more mixed-used and the density increases, the polluted area becomes enlarged, and the permeability reduces. The higher street network space is conducive to the diffusion of pollutants due to its better ventilation effect. When the street's height-to-width ratio (H/W) increases, the street's closedness is enhanced with the relative increase of the street-side buildings' height and seriously hinders the diffusion of pollutants. In the case of poor ventilation efficiency, it is easier to cause pollutants to accumulate, and the increase in building density reduces air circulation and makes it difficult for pollutants to diffuse [21].

2.3. High-Rise Opening Building

In recent years, in response to the dense population generated by rapid urbanization in Taiwan, environmental factors such as the landscape, building mass, configuration, and street layout in the city have gradually developed towards high-rise and high density, which hurts the original wind field of the city. Obstacles disturb the airflow and generate strong winds or no wind areas between the streets, which aggravate environmental problems such as the heat island effect and pollutant accumulation and seriously affect the pedestrian wind field and human comfort. They also influence the urban wind field and excavate its potential wind energy in the urban street profile to prevent achieving the goal of sustainable development.

For the study of the relationship between opening buildings and urban pollutant emissions, Hang et al. [22] confirmed that in high-rise compact urban areas, changing the proportion of buildings and open spaces and the height of building volumes increases the air permeability and affects the wind speed of the urban canopy. Research on high-rise opening buildings is divided into two parts.

One of them is the research and analysis of the building structure. For example, Li et al. [21] found that after openings were installed in high-rise buildings, the distribution law of floor wind became different and reduced the wind load of the building mass. Zhang et al. [4] pointed out that setting openings reduced the overall average wind load on buildings. However, it does not mean that the larger the opening, the more significant the reduction in wind load. Opening in the upper part of the building is beneficial to reduce the bending moment of the foundation while opening in the middle and upper part is more effective in reducing the average wind load. Xia et al. [5] studied the influence of wind characteristics on high-rise buildings with openings of different heights. They proposed that the wind speed must be the highest for the slit effect to be formed in the opening. The wind direction and the base bending moment have an influence, too. When the opening is located at 0.65 h, the lateral wind pressure coefficient is smaller, and the base bending moment decreases the most. Thus, opening at 0.65 h is the most favorable. Chen et al. [5] conducted a rigorous model force test on a high-rise opening building (0.5 and 0.85 h).

The results showed that the upper opening is better than the lower opening in reducing the average bending moment of the substrate, and the larger the opening ratio, the more obvious the effect.

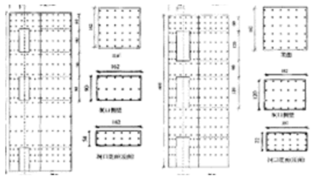
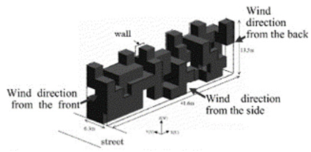
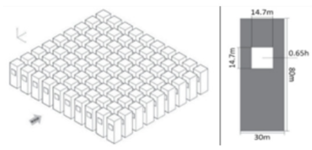
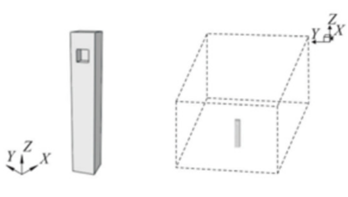
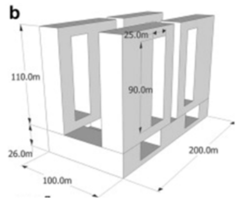
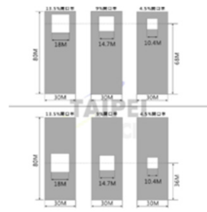
The second is a study on the impact of high-rise opening buildings on urban microclimate. Fourteen groups of plans were analyzed for the improvement benefits of high-rise opening buildings and the distance between adjacent buildings in the urban environment. For example, Chen [3] discussed the relationship between open high-rise buildings and the distance between different adjacent buildings. Li [7] discussed the effects of different openings (13.5, 9, and 4.5%) and opening heights (68 and 36 m) on the urban wind, temperature, and pollutant concentration. Yeh [8] designed a total of twenty simulation cases based on different building and street space forms (height of openings, street aspect ratio, and building orientation) and planting configuration (green coverage). Furthermore, he discussed the impact of different architectural design cases on the urban microclimate. Voordeckers et al. [23] aggregated more than 200 studies covering different configuration variables (street canyons, buildings, and in-canyon configurations). Nineteen urban planning strategies were formulated to adjust for different building forms (Table 1).

Table 1. High-rise Opening Building cases.

Legend				
name	Hysan Place	South Korea Amore Pacific	OUE Twin Peaks	Baohui Qiuhonggu
year	2012	2017	2015	2015
high	36F.4B/204 m	22F.7B	35F	41F.4B/160.98 m
opening	Multiple rectangular	middle square	right square	middle rectangular
address	500 Hennessy Road, Causeway Bay, Wanchai District, Hong Kong Island	Yongsan District, Seoul, South Korea	33 Lianni Hill Road, Singapore	No.166, Shicheng North 6th Road, Xitun District, Taichung City, Taiwan

From the above literature review, it is known that high-rise opening buildings have a significant effect on urban ventilation. However, in the past, research mainly focused on the building structure, bending moment, and surface wind pressure. The relevant research on the impact of urban microclimate still carries out numerical simulation analysis on the air penetration height, air penetration opening ratio, and the same building height. Thus, it is necessary to explore the impact of different opening patterns in high-rise buildings on urban wind fields and NOx emission study as shown in Table 2.

Table 2. Different patterns high-rise open-building Simulation program.

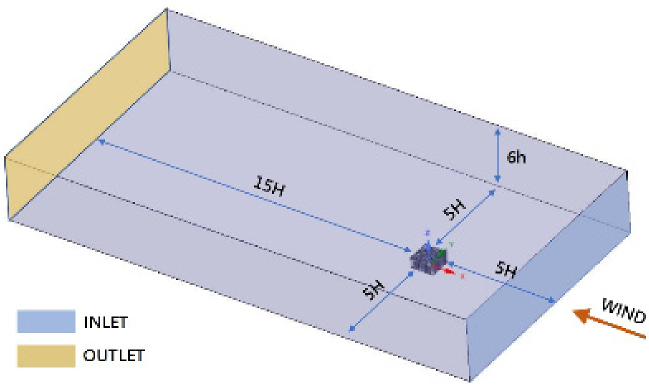
Single Building	Multiple Building	10*9Array Building
		
Three Openings [4]	Multiple Openings [24]	Single Opening [3]
		
Single Opening [5]	Multiple Openings [25]	Single Opening [7]

3. Research Design

In this study, ANSYS Fluent 18 is used to simulate operations with CFD. The required spatial boundary range needs to maintain an appropriate distance from the building volume to ensure the accuracy of the numerical calculation results with the size of the model calculation domain (Computational Domain) set. The entrance and lateral boundaries must be at least 5 H away from the model (H is the length of the long side of the overall building model). The exit boundary must keep a distance of more than 10 h, and the height of the highest building model from the top boundary must be at least 5 h (h is the highest building height) to achieve a complete flow field as shown in Table 3. The meteorological parameters are set based on the 10-year summer meteorological data from the Taipei Station (466920) from 2012 to 2021. The annual average wind speed is 1.92 m/s, the wind direction is east, and the annual average temperature is 29.67 °C. The inlet is the wind speed gradient ABL Profile, the outlet is atmospheric pressure, and the ground roughness is 0.016 m.

Table 3. Boundary Condition.

Wind	**Velocity**	**Temperature**	**NO_2**	**Mesh**	**Ground**	**Element Size**
East	1.92 m/s	29.67 °C	649 ppb	32 million	0.016 m	1 m



The opening rate of the building facade is 9% according to the research of Zhang et al. [4]. This study refers to the 6 × 6 ideal city case of Li et al. [9] as the setting basis, and the research range is 330 × 330 m as shown in Figure 1. Referring to domestic and foreign cases of opening buildings, each building unit is 30 × 30 × 160 m, and four types of openings are designed as shown in Figure 2 and Table 3. The opening height is 0.45 h according to the research of Xia et al. [5] and Yeh [8] (h is the height of the building). The square and rectangular openings' dimensions are 21 × 21 m and 10 × 44 m as shown in Figure 2.

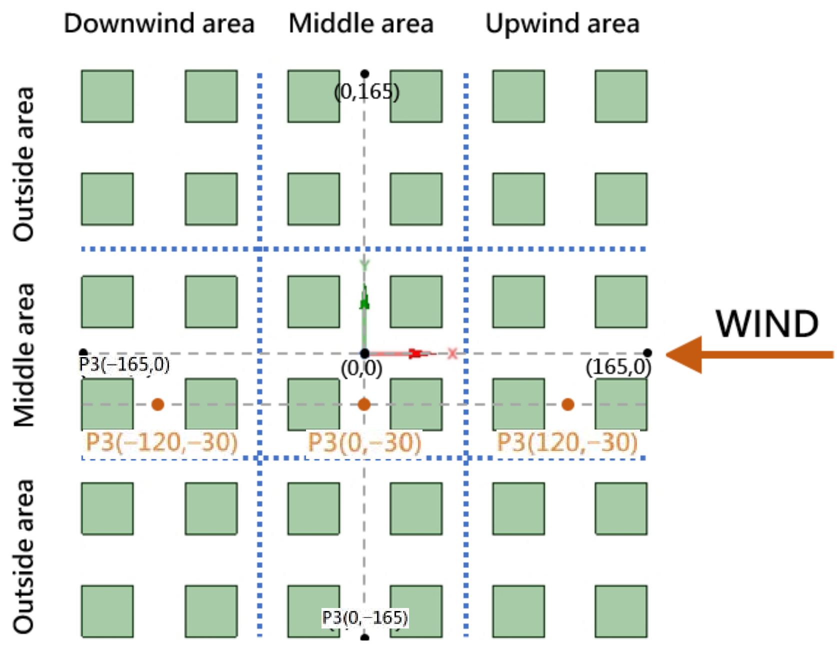


Figure 1. Ideal city and measuring point.

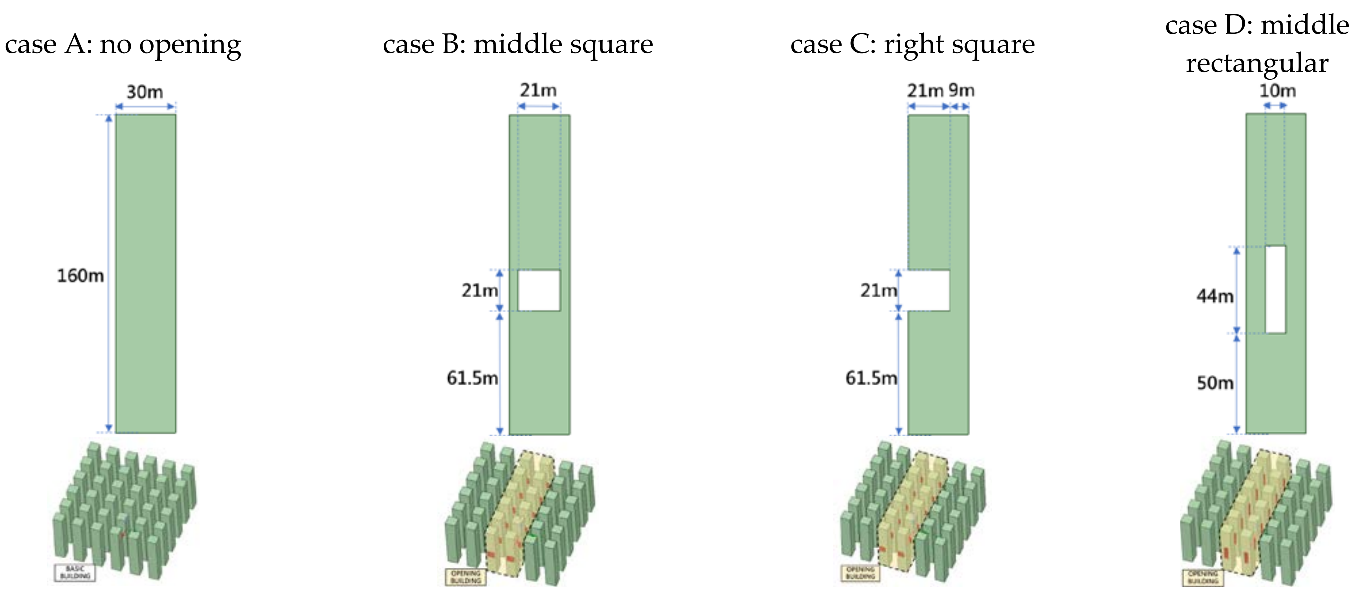


Figure 2. High-rise opening building cases.

4. Simulation Analysis

4.1. Wind Field Simulation Analysis

For simulation, a 1.5 m pedestrian floor and a 72 m high floor (at the center of the opening) were used. The analysis of wind speed measurement points is carried out as follows:

- At a high floor of 72 m, case A does not have an opening. When the building facade is perpendicular to the flow of people, the windward area of the building is more extensive than in other cases of the opening building. Thus, the obstruction to air circulation is relatively large, resulting in a high degree of wind speed attenuation. The average wind speed at the leeward and downstream buildings of the affected buildings is low. At the 72-m high floor, the wind speed of P1 is 1.3 m/s, the wind speed of P2 is 0.82 m/s, and the wind speed of P3 is 0.12 m/s. In contrast, cases B, C, and D with openings reduce the obstruction of air circulation due to the increased ventilation cross-section and the Venture Effect of the opening, and the overall wind speed has a significant effect. Case B (middle square opening) is at a high floor of 72 m, the wind speed of P1 is 4.37 m/s, and the wind speed of P2 is 2.72 m/s. The wind speed of P3 is 1.59 m/s, and the opening is 72 m; the upper and lower street canyons generate a wake, which is beneficial to urban ventilation. For case C (the right side of the square is open), the wind speed of P1 is 3.93 m/s, the wind speed of P2 is 2.17 m/s, and the wind speed of P3 is 1.57 m/s. Because the opening is on the right side of the building, the windward side is the smallest, which effectively allows the wind to flow in, so the wind speed attenuation at the end of P3 is the least among all the cases. In case D (the center rectangle is open), the wind speed of P1 is 3.8 m/s and that of P2 is 2.03 m/s. The wind speed of P3 is 0.59 m/s. Since the opening length is the longest and is close to the ground, the air flows through the opening. It hinders the downstream building facade and generates a windward vortex, which increases the street canyon. The vertical airflow flows, thus reducing the flow velocity at the upper floors and increasing the flow velocity at the pedestrian level. Hence, the wind velocity at the end of P3 is lower than that of cases A and B. The above analysis result shows that at a high floor of 72 m, the ventilation benefit is case B > case C > case D > case A.
- At 1.5 m from the pedestrian level, since case A does not have an opening, the wind bounces in the street canyon between the buildings to generate windward eddies when the building facade is perpendicular to the flow of people. However, in the urban canopy, the wind speed at the layer is significantly attenuated, but it can make the airflow into the pedestrian layer. The wind speed of P1 is 0.86 m/s, the wind speed of P2 is 0.62 m/s, and the wind speed of P3 is 0.45 m/s. For case B, the wind speed at P1 is 0.52 m/s, the wind speed at P2 is 0.34 m/s, and the wind speed at P3 is 0.27 m/s. For case C, the wind speed at P1 is 0.55 m/s, the wind speed at P2 is 0.25 m/s, and the P3 wind speed is 0.23 m/s. There is little difference in wind speed between the two cases. The openings on the facade significantly increase the wind speed of the upper floors, and the wake forms at the upper and lower parts of the building openings, which is beneficial to the ventilation of the urban canopy. It flows into the pedestrian layer and causes an apparent weak wind area. For case D, the wind speed of P1 is 0.49 m/s, the wind speed of P2 is 0.44 m/s, and the wind speed of P3 is 0.39 m/s. The opening length is long and close to the pedestrian layer. Therefore, the wind speed on the upper floors is higher than that of case A, and the vortex formed under the building opening is closer to the ground so that the wind speed of the pedestrian floor is better than that of cases B and C. The above analysis result shows that at the pedestrian level of 1.5 m, ventilation benefits are in the order of case A > case D > case B > case C (Figure 3).

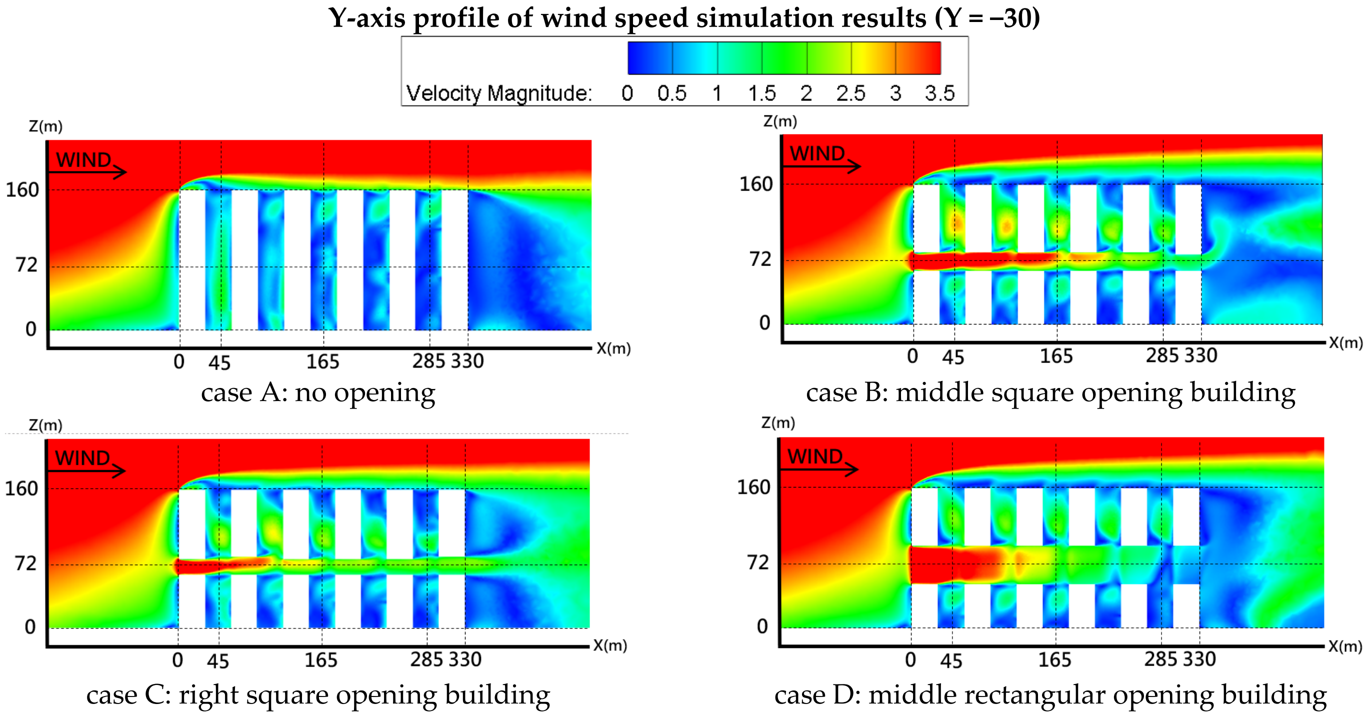


Figure 3. Profile of wind speed simulation results.

4.2. NO_2 Field Simulation Analysis

The 1.5 m pedestrian floor, the 30 m middle floors (the average height of the pedestrian floor and high floors), and the 61.5 m high floor (the height of the lower edge of the opening) were used as pollutant measurement points for analysis (Figure 4 and Table 4).

4.2.1. Case A: Without Opening

In the absence of air-permeable openings, with the building facade perpendicular to the flow of people, the X-axis street parallel to the wind direction is the place with the highest overall wind speed, which carries pollutants away from the street area. The areas with a higher concentration of pollutants were mainly concentrated in the lee of the building. At a 1.5 m pedestrian level, the concentration of pollutants in the lee of the front end of the city was the lowest. As a result, the pollutant concentration gradually increased. In contrast, the pollutants at the height of 30 m on the middle floor and 61.5 m on the upper floor were mainly concentrated in the urban end area. However, the distribution of pollutant concentration decreased with the increase of the Z-axis height.

4.2.2. Case B: The Middle Square Opening

In case B with air openings, because of the increase of the ventilation section, the obstruction of air circulation was small, and the windward vortex was formed above and below the opening so that the heights of 30 and 61.5 m benefited from the increased wind speed of the air openings. Effective diffusion of pollutants and pollutant removal were better than that of case A without openings. Nevertheless, because the building floor was too high, a weak wind area was generated at the 1.5 m pedestrian level, causing pollutants to accumulate at the end of the city—the lee of the building along the X-axis street in the area.

4.2.3. Case C: Right Side Square Opening

For case C with an air-permeable opening, the obstruction of air circulation is small due to the increase of the ventilation section. A windward vortex was formed above and below the opening. The heights of 30 and 61.5 m benefited from the increased wind speed of the air-permeable opening. Pollutants were effectively diffused. However, because the opening was located on the right side, the airflow in the street flew out directly, and the Venturi effect was weak. The pollutant removal effect was worse than that of the middle opening case B, and the building floor was too high. The height was far from the ground, a weak wind area was generated at the pedestrian level of 1.5 m, and pollutants were not effectively diffused. Hence, pollutants accumulated in the leeward of buildings and X-axis streets in the urban end area. Regardless of different heights (1.5, 30, and 61.5 m), the accumulation of pollutants was higher than in the other open cases (cases B and D).

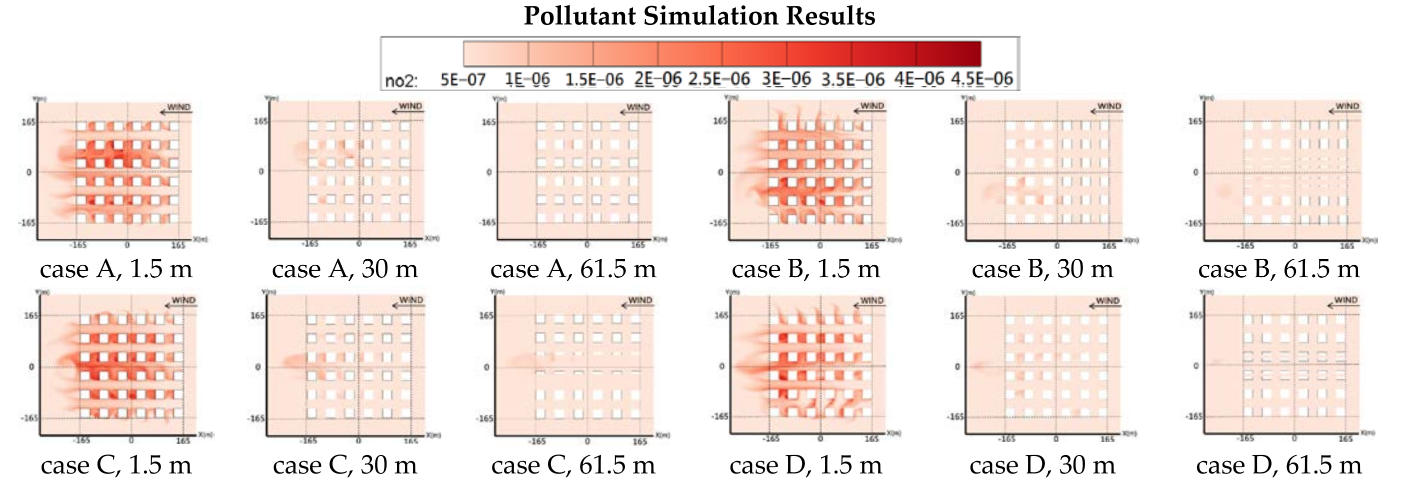


Figure 4. Floor plan of pollutant simulation results.

4.2.4. Case D: Rectangular Opening

In case D with a rectangular air-permeable opening, because the opening was long and narrow and adjacent to the pedestrian floor, the airflow entered the street canyon more effectively under the Venturi effect and was affected by the downstream building facade. The area where pollutants were gathered, so the removal effect of pollutants at different heights was better than the other opening solutions (cases B and C).

Table 4. Distribution characteristics of pollutants in street Canyons with different heights.

Height	Pedestrian Level 1.5 m	Middle Floor 30 m	High Floor 61.5 m
Street Canyon Space	continuous and closed	continuous and closed	0.45 h square opening's lower edge
Pollutant Distribution	continuous linear pollution	Small blocks gather at the end of the city	Dotted and scattered at the end of the city
Pollutant Concentration	Wide range and high concentration	Low concentration in local area	Low concentration in sporadic areas

5. Conclusions

This study simulates urban wind and pollutant changes using ideal cities. Future research should consider real urban factors like climate, design laws, and opening heights. The focus is on how various high-rise building openings affect the urban environment.

5.1. Wind Speed Distribution

Case A, without opening, had the largest area on the windward side, and the wind speed hindered the air circulation on the upper floors, so the wind speed was the lowest among the cases at 72 m. Overall, there was little difference in wind speed in case B with a square in the middle, and, in case C, with a square on the right. However, the wind speed of case C was slightly lower than that of case B at 1.5 m from the pedestrian level. Case D had the most extended opening length so that the eddy current formed under the building opening became closer to the ground, making it easier for airflow to enter the pedestrian floor from the high floor. Therefore, the wind speed of case D was better than that of the opening cases B and C for the pedestrian floor. The wind speed was much faster than the no-opening case A. Overall, case D was the optimal ventilation case.

5.2. Concentration Distribution of Pollutants

Pollutant distribution was influenced by wind speed, causing pollutants in case A to concentrate downwind of the building. Conversely, cases B and C saw pollutants concentrated in the middle and lower city layers, with cases B and C's middle and upper floors particularly affected. Effective airflow through vents limited ground-level contaminant spread. Case D, with the most extensive opening near the pedestrian floor, created a vortex evacuating pollutants, presenting an optimized solution for pollutant removal.The conclusions and suggestions of the four simulation cases for no-opening and different types of opening buildings are as follows.

1. The Opening Building Improved the Permeability of the Street and Air Circulation and Increased the Pollutant Removal Effect

The air-permeable of the opening building facade increased the ventilation section. It improved the permeability of the overall street in the city, significantly increasing the wind speed on high floors. The wind speed reached the maximum value at the opening. However, because the building height was too high (160 m), it was difficult for the eddy current under the opening to enter the pedestrian layer, resulting in the weak wind area affecting the pedestrian wind field.

2. Different Opening Types Affected the Diffusion of Pollutants

The rectangular opening was the best optimization case for removing pollutants at different heights (1.5, 30, and 61.5 m). There was little difference in wind speed and pollutant concentration field between cases B and C which had square openings. However, the wind speed benefit of rectangular openings at 1.5 m of the pedestrian level was better than others. This case benefited from its narrow and long opening adjacent to the street traffic pollution source. The vortex generated by the airflow flowing through the opening in the street canyon improved the diffusion of pollutants.

3. Affected by the Distance from the Pollution Source and the Space of the Street Canyon, the Distribution of Pollutants Changed with the Height of the Z-Axis

Pollutants gradually dispersed and decreased in concentration as the height increased. The pollutant distribution was continuous, linear, and high in concentration at 1.5, 30, and 61.5 m. The wind speed increased due to the adjacent openings. The pollutants diffused into several small blocks at 30 m, and the pollutants diffused at 61.5 m in sporadic distribution.

4. The Wind Speed of Street Canyons at the End of the City Decreased with the Increase in the Number of Buildings

The continuous and long streets hindered air circulation, making it difficult for the wind to penetrate the end of the city and resulting in the inability of pollutants to diffuse naturally through air convection. Therefore, in addition to penetrating the building facade, it is necessary to avoid excessively long streets and leave open space appropriately to achieve the ideal ventilation effect and reduce the accumulation of pollutants in the street canyon. It is necessary to develop a city sustainably under the high-rise and high-density development mode.

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