

Article

Pedestrian-Level Wind Environment Assessment of Shenyang's Residential Areas through Numerical Simulations

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Abstract: In recent decades, increasing urbanization has increased construction land shortages, which has made people pay more attention to the utilization of vertical space. The emergence of more and more high-rise buildings has affected the wind environment at the pedestrian level, especially in residential areas. In this research, the typical patterns of the layouts of residential buildings in Shenyang were investigated and summarized, and the wind environment of the residential areas of different architecture layouts was simulated according to the climatic conditions in Shenyang. After analyzing the simulation results, a typical layout mode for the residential areas in Shenyang was developed to facilitate the establishment of a favorable wind environment. In comparison with different building layouts, a staggered layout of slab buildings, half-enclosed layout of point buildings with openings on the south side, slab-point combined buildings with slab buildings on the north side, and point buildings on the south side were found to be the most suitable layouts for Shenyang's climate. Thus, this study can provide guidance to designers and urban planners in addition to practical suggestions for residential planning.

Keywords: wind environment; residential areas; simulation; cold region



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1. Introduction

In Chinese megacities, residential areas are among the most important activity spaces in urban areas. Outdoor ventilation in residential areas is an essential part of urban microclimate studies [1]. At present, the residential areas in many Chinese megacities are composed of high-rise buildings, leading to excessive instantaneous wind speeds in some areas. High wind speeds at the pedestrian level can lead to uncomfortable or even dangerous conditions [2–6]. Lawson and Penwarden (1975) have reported the death of two old ladies due to an unfortunate fall caused by high wind speed at the base of a tall building [7]. Therefore, many government agencies have been studying new policies to improve comfort and safety with regard to high wind speeds around buildings. Moderate wind environments can improve human comfort, facilitate the diffusion process of pollutants, contribute to energy conservation, and decrease urban heat islands [2,8–14]. In large urban communities, many urban planners have found it necessary to discuss wind conditions at the pedestrian level in the initial design stage [15–17]. Therefore, it is quite important to evaluate wind comfort at the pedestrian level and have an acceptable wind environment from the development perspective of urban planning.

Shenyang is located in the northeast of China, where winter is long and very cold. This region is described as a severe cold region in the code for thermal design of civil buildings, GB 50176-2016 [18]. In winter, strong wind contributes to the degree of discomfort, especially in severe cold areas. Therefore, it is essential to obtain convenient wind environments in severe cold regions from the human comfort perspective. Liu et al. investigated a prediction model of the pedestrian-level wind chill temperature of the high-rise residential

areas in China and proposed a pedestrian-level thermal sensation evaluation method for six major cities in the severe cold regions in China [19]. Jin et al. studied the influence factors of thermal comfort at the pedestrian level in the severe cold regions of China and suggested that optimization in winter should be focused on blocking wind [20]. Yang et al. considered 31 cities in China as examples to investigate the relationship between urban ventilation and energy demand from a thermal environment perspective and indicated that good ventilation can reduce energy demands in summer and increase them in winter [21]. These studies mainly focused on the contribution of urban ventilation to thermal environments and showed that it is important to control the pedestrian-level wind environment in residential areas of the severe cold regions in China.

There are three main types of residential plans in China: determinant layout, enclosing layout, and mixed layout. Residential areas generally cover large areas and have regular layouts. Shui conducted a questionnaire survey on human wind comfort in seven typical residential areas and suggested that the enclosing layout and mixed layout are suitable for the multistory residential areas in severe cold regions [22]. Although several studies on the wind conditions at the pedestrian level in the cold regions of China have been explored in prior work, most of these studies have focused on specific residential areas. However, the classification of residential areas needs to be more comprehensive. It takes time to simulate the wind environment of each residential area in the early design stage. One good solution is to simplify the current residential layouts into several typical ones for wind environment assessments, which can make it convenient for architects to choose suitable layouts for their in-depth designs.

Considering the current trend that more and more high-rise residential areas are being built in Shenyang, 12 typical layouts of newly built high-rise buildings were summarized in this study, and the wind environment of each layout was assessed. Additionally, in this study a layout mode of residential areas that can facilitate favorable wind environments in Shenyang was established using a computational fluid dynamics (CFD) simulation. First, the typical patterns of the residential district layouts in Shenyang, through which the simulation samples were selected, were investigated and summarized. Then, the wind environment of residential districts was simulated according to the climatic conditions in Shenyang, and the simulation results were analyzed using Chinese green building evaluation standards. Finally, an architectural layout suitable for the climate conditions in Shenyang was put forward. Overall, this study provides more architectural layout choices for the cold regions of China. It also provides practical suggestions for urban residential planners.

2. Literature Review

2.1. Effects of the Architectural Geometric Factors

Scholars from all over the world have considered building layouts, building orientation, street canyons, and many other factors influencing the wind environment at the pedestrian level around buildings. A great deal of research has been done, providing valuable references for follow-up research. In the initial design stage of Tel Aviv's new business district, the Israeli architect Cape took sunshine, wind direction, wind speed, and other climatic factors into consideration and proposed a new design process for reducing the impact of sunshine on building groups, urban roads, and business districts [23]. This project could provide the business district with a suitable wind environment and also meet the residents' requirements. Allegrini, J et al. analyzed microclimates by studying six different urban topologies, and only the building heights of the individual buildings were changed [24]. The results showed that building height changes can have an obvious impact on the surrounding microclimate and that the temperature changes around buildings are related to the surrounding airflow and heat diffusion efficiency. Stathopoulos T. indicated that circular and polygon-shaped building corners improve wind climates compared with square-shaped corners due to the reduced downwash [25]. Some other professors have concentrated on wind conditions when buildings and the wind direction have different

angles and indicated that the wind resistance of small angles is weak, which increases wind velocity [26,27].

2.2. Effect of Architectural Spatial Morphology

In urban design, different spatial morphologies not only affect traffic but also result in different microclimates. The appropriate arrangement of buildings can facilitate comfortable wind environments for pedestrians. Some experts have focused on climate-sensitive design in tropical areas and put forward a method for improving urban climate and reducing energy consumption through urban design. They have also conducted analyses on how to use architectural layout designs to reduce the impact of the urban heat island effect, promote the improvement of microclimates around buildings, and contribute to urban environments, providing theoretical bases for related research in other regions with different climates [28]. Gordon B. et al. studied the relationship between the density of residential buildings and wind environments through satellite images on GIS. They concluded that the wind environment in residential areas is affected by the density of residential buildings and that the wind speed in the urban areas with high building density would be lower [29,30]. Kubota et al., Taleghani et al., and Mehdi S. et al. conducted pedestrian-level wind condition analysis on several typical residential layout modes in Japan, the Netherlands, and the UK [31–33], and building arrangements for optimal wind environments for many areas in these countries were proposed.

2.3. Wind Environment Studies in China

With the acceleration of urbanization in China, more and more high-rise buildings are designed for economic reasons and also to save construction land. At the same time, urban residents have requirements for comfortable and safe environments. Thus, the outdoor wind environment in residential areas has gradually attracted the attention of experts. Zhang et al. conducted a CFD simulation and a wind tunnel study to explore wind conditions around different building layouts, and they found that staggered arrangements facilitate more wind into residential sites, which improves natural ventilation in residential areas [34]. Some experts in Nanjing and Chongqing pointed out that the scattered point layout is helpful for ventilation due to less site coverage [35,36]. Shui et al. performed experiments on the wind conditions of seven residential areas and found that the multistory residential areas with hybrid-type and enclosed-type layouts are suitable for China's severe cold regions [22]. The papers published include a vast number of papers concerning the wind environments at the pedestrian level in residential areas. However, more studies were conducted in southern China than in other regions.

2.4. Codes and Standards in China

According to the planning characteristics of the spatial morphologies of the residential areas in China, the government has published some evaluation standards and planning restrictions. Design standards for the thermal environments of urban residential areas suggest that in the first, second, sixth, and seventh building climate zones, the residential areas with high building density should be arranged in the upwind direction of the dominant wind direction in winter. Additionally, in the third, fourth, and fifth building climate zones, the residential areas with high building density should be arranged in the downwind direction of the dominant wind direction in summer [37]. The assessment standards for green buildings suggest that in winter, the wind speed and wind velocity ratio at the pedestrian level should be lower than 5 and 2 m/s, respectively, and that the wind pressure difference between the windward and leeward sides of a building should be less than 5 Pa. This way, the penetration of cold air into rooms can be reduced. In summer, there should be no windless zones in residential quarters, which affects the heat dissipation of buildings and the dissipation of pollutants. The difference in wind pressure between the inner and outer surfaces of windows should be higher than 0.5 Pa, which is very beneficial to natural ventilation [38].

The shortcomings in the previous research on the urban wind environments in residential areas can be summarized as follows:

- (1) Due to the restrictions of economic factors, more and more high-rise residential areas have been built in China. At present, there is a lack of simulations and comparisons concerning the wind environment in the planning modes of high-rise residential areas, especially in the severe cold regions in China.
- (2) Some of the current wind environment research works are mainly at a macroscopic scale and do not adhere to government standards and codes.

This paper comprehensively summarizes the design of high-rise residential quarters in Shenyang and simplifies them into a more intuitive model. Through a numerical simulation, residential layouts with favorable pedestrian-level wind conditions were obtained for Shenyang's climate condition. The research results can directly guide architectural designs from the perspective of the urban wind environment.

3. Materials and Methods

3.1. Study Area

Shenyang is the capital of Liaoning Province, which is the economic, cultural, financial, and commercial center of Northeast China. It is also an important industrial base and a historical and cultural city in China. Shenyang is located in the south of Northeast China ($42^{\circ}21' N$, $123^{\circ}28' E$), and it has a continental monsoon climate in the north temperate zone. Thus, it is cold in winter and warm in summer. The cold period is long, as spring and autumn are short and windy; the temperature differences between the seasons are also obvious in Shenyang. The annual mean temperature and humidity are $8.1^{\circ} C$ and 63%, respectively. Figure 1 shows the wind map of Shenyang, from which it can be seen that the wind direction is relatively stable all year round and that the maximum wind direction is mainly from the south in summer and north in winter.

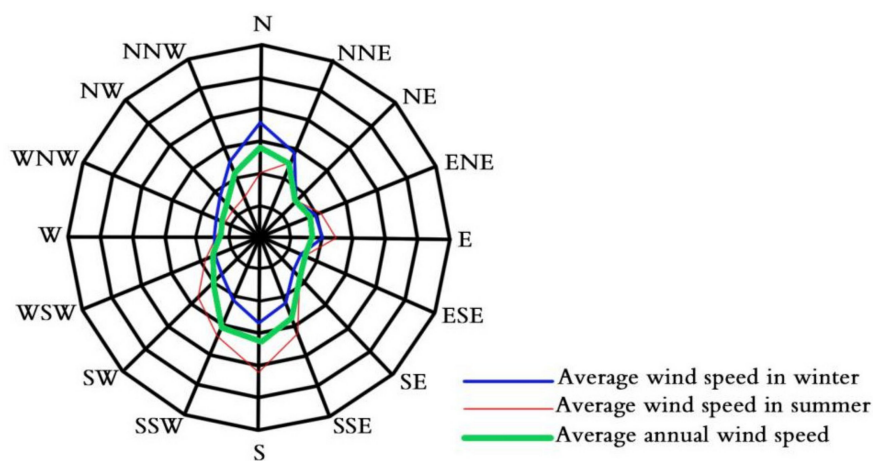


Figure 1. Wind map of Shenyang (data source: Architectural Design Data Set of China [M] Beijing, 2017).

3.2. Methods

In this paper, the CFD Fluent software was used to simulate the building wind environments of different architectural layouts. By investigating more than 50 residential areas in Shenyang, it was found that the newly built residential areas in Shenyang mainly comprise slab buildings, point buildings, and slab-point combination buildings (Figure 2). The design standard for energy efficiency of residential buildings in severe cold and cold zones proposes that the building orientation should be north–south or close to north–south [39]. In the cold areas of China, the orientation of residential buildings in the whole city is relatively fixed, and most of them are in the north–south orientation, which can also be seen from the survey results (Figure 2). Therefore, we defined the simulated buildings as

having the north–south orientation. The uniform standard for design of civil buildings defined that the height of high-rise residential buildings is between 27 m and 100 m [40]. The code for fire protection design of buildings divides the high-rise buildings into two categories, one being 54 to 100 m, and the other 27 to 54 m [41]. The former requires higher fire protection than the latter, and some building developers will limit the height of the building to 54 m. Together with parapet and other components, the total height of the building is about 60 m.

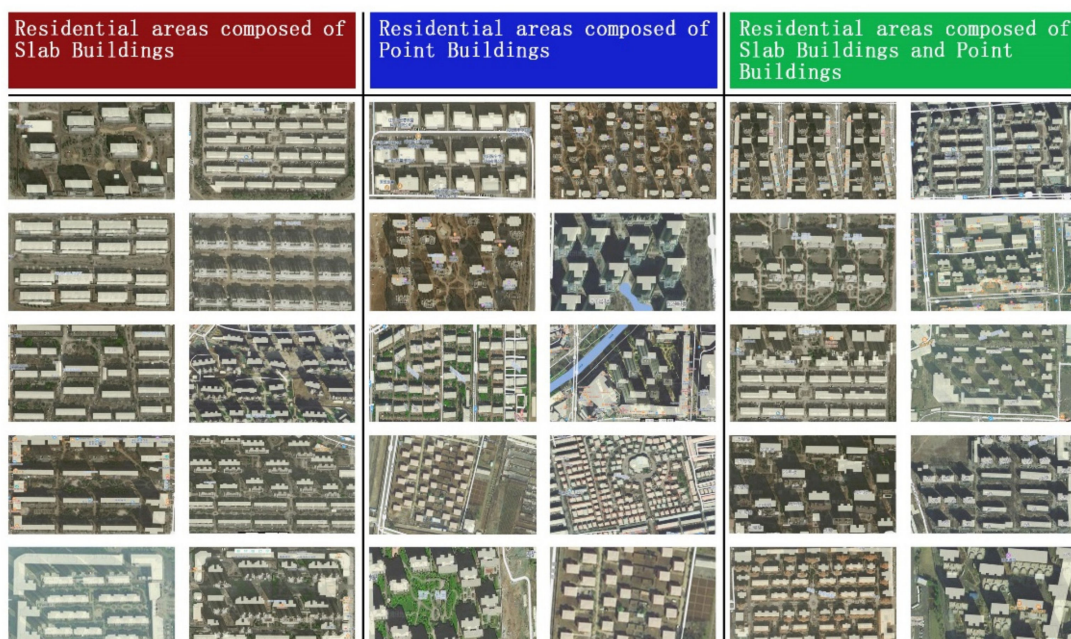


Figure 2. Some high-rise residential areas in Shenyang (data source: drawn by author).

Slab buildings and point buildings are two common forms of high-rise buildings in China [42]. It can be seen from Figure 2 that there are three kinds of residential areas in Shenyang; the first one is composed of slab buildings, the second is composed of point buildings, and the third is composed of both slab buildings and point buildings. It can be seen from Figure 3 that the length of a slab building is far greater than its width and that a slab building looks like a slab in a general plan. However, for point buildings, the length and width are the same; also, a point building looks like a square point in a general plan. Each flat in a slab building has a larger building area, while a point building is smaller. These two architectural forms are more common in Chinese cities in order to meet the needs of different households. By analyzing and comparing the wind velocity ratio, wind velocity vector map, and wind pressure at the pedestrian level, the relationship between the wind environment and plane layouts could be obtained. In addition, a wind pressure diagram was used to analyze the heat preservation of the building envelopes, providing references and evaluation bases for planning the layouts of the residential areas in Shenyang.

Nowadays, the construction departments of Shenyang encourage the construction of high-rise buildings in the city center for economic reasons and also to save construction land. However, more and more high-rise buildings may cause complex wind environments. In winter, when the temperature is low, the high wind speeds in residential areas may cause discomfort to pedestrians. In this study, this situation was mainly considered. Thus, winter was chosen to be the main evaluation season. According to the Architectural Design Data Set of China [43], the dominant wind direction in winter is north, and the average wind velocity is 3.0 m/s.

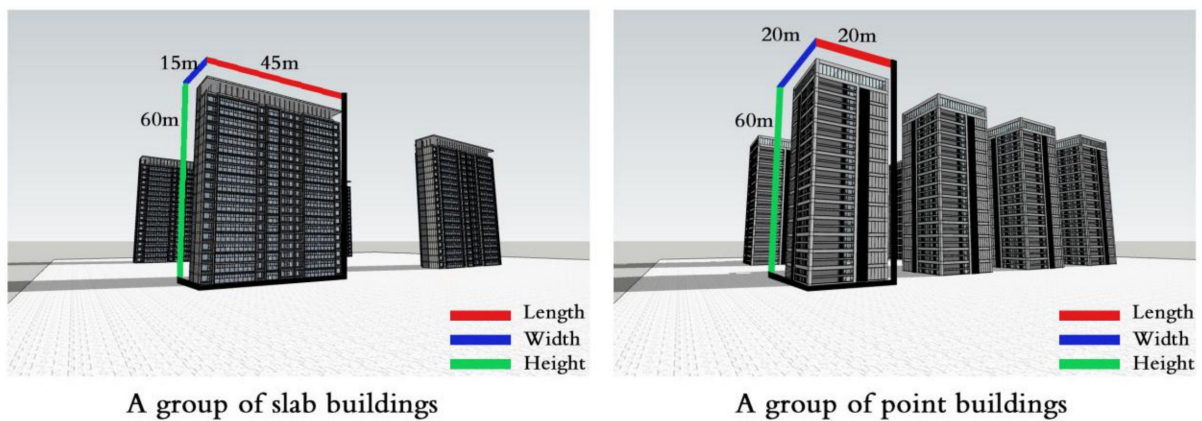


Figure 3. Slab buildings and point buildings (data source: drawn by author).

3.2.1. Computational Domain and Grids

The calculation area size directly affects the simulation accuracy. If the calculation area is small, the flow field can be distorted. A large calculation area would result in many grids and increase the calculation amount and cost. According to relevant experience at home and abroad, the simulation area was set to $360\text{ m} \times 500\text{ m}$, and the calculation height was set to five times the building height [22,44,45]. The outdoor airflow at the bottom of the atmosphere is generally in the range of low-speed flow, and air can be assumed as Boussinesq, which is a viscous and incompressible fluid. Generally, the CFD software is equipped with various turbulence models, and the $k-\epsilon$ model is the most widely used one in engineering applications. This model has a low calculation cost, small fluctuations, and high precision with regard to numerical calculations [46]. The DB11/938-2012 Standard for Green Building Design (Beijing) suggests that the standard $k-\epsilon$ model can be used when the calculation accuracy is not high and only a flow field at a height of 1.5 m is concerned [47]. Therefore, the standard $k-\epsilon$ model was selected in this study, and the GAMBIT preprocessing software from Fluent was used for grid division. Line grids and area grids were divided for the buildings and peripheral large-scale computational domains. The dense grids were arranged near the solid areas, the sparse grids were adopted in the areas far away from the model, and all the grids were triangles. A reference pressure position was set due to the incompressible flow. Regardless of the gravity influence, the operating pressure was set to the standard atmospheric pressure of 101,325 Pa.

3.2.2. Building Arrangements for Simulation

According to the typical building layout conditions and the city policies in Shenyang, this study summarized 12 kinds of layouts for the numerical simulation. Two kinds of buildings were simplified into regular quadrangles before the simulation, and the sizes of the point and slab buildings were set to $20\text{ m} \times 20\text{ m} \times 60\text{ m}$ (length \times width \times height) and $45\text{ m} \times 15\text{ m} \times 60\text{ m}$, respectively. The specific arrangement is shown in Table 1.

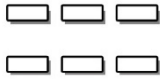
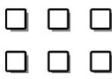

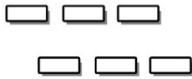
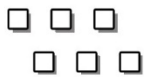

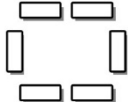
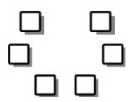

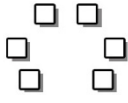

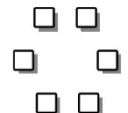
3.2.3. Evaluation Standard of the Wind Velocity Ratio

In practical applications, the wind velocity ratio (wind speed amplification) is used as a comfort parameter to discuss the comfort of wind environments around buildings [38]. The wind velocity ratio reflects the degree of wind velocity change caused by the existence of buildings. The wind velocity ratio R_i is defined as follows:

$$R_i = V_i/V_0$$

where R_i is the wind velocity ratio at the position of point i (dimensionless), V_i is the average wind velocity at the pedestrian height at point i in the flow field, and V_0 is the average wind velocity of the undisturbed incoming flow at the pedestrian height (generally the initial wind velocity).

Table 1. The building arrangements for the simulation.

Type	Slab Buildings	Point Buildings	Slab-Point Combination Buildings
A			
B			
C			
D			
E			
SIZE (Length × Width × Height)	45 m × 15 m × 60 m	20 m × 20 m × 60 m	45 m × 15 m × 60 m 20 m × 20 m × 60 m

The wind velocity ratio evaluation is a common evaluation standard of wind comfort. This study used this index to discuss the outdoor wind environment comfort of Shenyang's residential areas under different arrangement forms.

4. Results

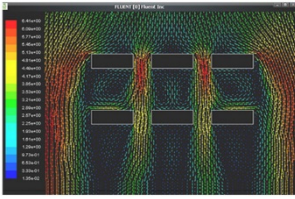
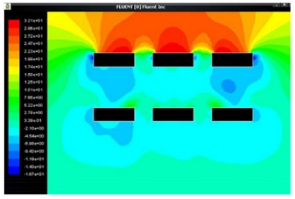
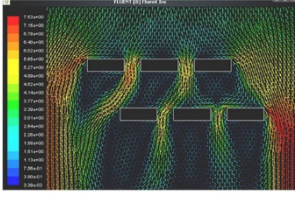
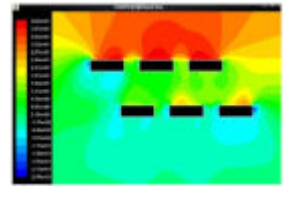
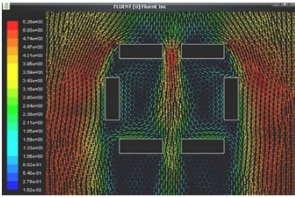
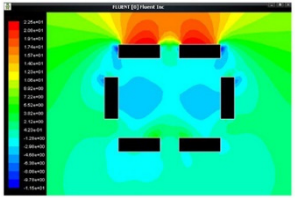
4.1. Arrangement of the Slab Buildings

Hereinafter, SB is used to represent slab buildings. The wind vector and wind pressure results of SB(A), SB(B), and SB(C) are shown in Table 2.

SB (A) is a plane with six slab buildings in a parallel arrangement. In winter, the airflow coming from the north is weakened when encountering the buildings, and the wind velocity ratio on the windward side of the buildings is 0.43. However, the wind velocity at the corner of the buildings is increased, and the wind velocity ratio is 1.18. Two channel winds are formed between the sidewalls of the three buildings in the first row, and the wind velocity ratio is 2.77. When air flows to the second row of buildings, the wind effect in the channel between the sidewalls is less significant than that in the first row of buildings, and the wind velocity ratio at the channel is 1.67. The pressure difference between the windward and leeward sides of the first row of buildings is larger than that of the second row of buildings, and almost all of the second row of buildings are in an area with negative pressure, but there is a very small area with positive pressure at the corner.

SB (B) is a plane with six slab buildings in a staggered arrangement. The simulation results of SB (B) are similar to those of SB (A). The wind velocity ratios at the windward side, building corner, and two passages between the sidewalls are 0.50, 1.38, and 2.26, respectively. The wind effect of the second row of buildings' passage is weakened, and the wind velocity ratio is 1.40. The pressure difference between the windward side and leeward side of the first row of buildings of SB (B) is still relatively large but smaller than SB (A). The range of the area with positive pressure on the windward side of the second row of buildings is increased.

Table 2. The simulation results of slab buildings.

Slab Buildings	Wind Vector	Wind Pressure
SB (A)		
SB (B)		
SB (C)		

SB (C) is a plane with six slab buildings in an enclosed arrangement. It can be seen from the results that the wind velocity ratios at the corner of the first row of buildings and at the channel between the sidewalls of the buildings are 1.17 and 1.6, respectively. Most of the site's areas have low air velocity. The pressure difference between the front and back of the first row of buildings is large, and there are two large-scale and high-intensity low-pressure areas in the enclosed courtyard behind them.

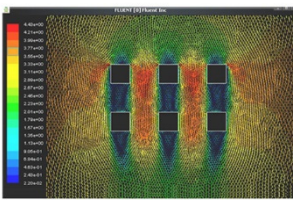
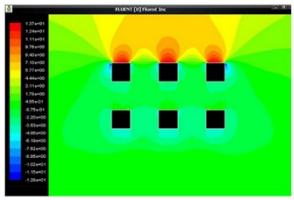
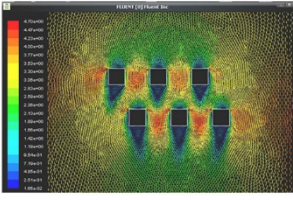
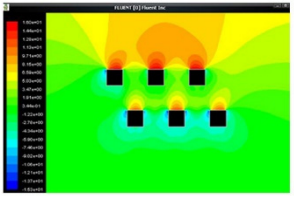
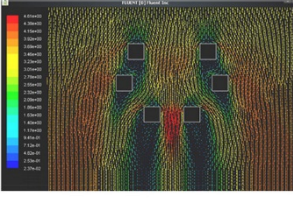
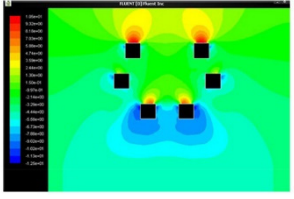
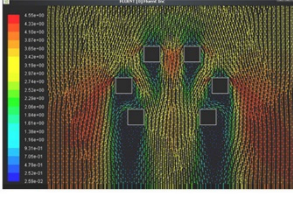

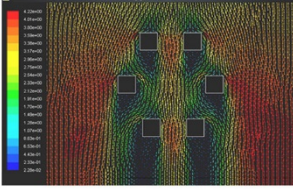
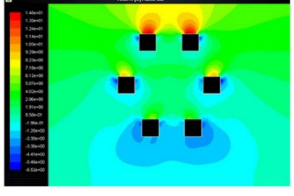
4.2. Arrangement of the Point Buildings

PB was used to represent the point buildings hereinafter. The wind vector and wind pressure results of PB (A), PB (B), PB (C), PB (D), and PB (E) are shown in Table 3.

PB (A) is a plane with six-point buildings in a parallel arrangement. In winter, the airflow coming from the north is weakened when encountering the point buildings, and the wind velocity ratios at the windward side and the corner of the buildings are 0.22 and 1.4, respectively. The channel wind velocity ratio of the first row of buildings is 1.47. Due to the shelter of the first row of buildings, the wind velocity on the windward side of the second row of buildings is low, but the wind velocity ratio at the passage is still high (~1.27). In addition, the pressure differences between the front and back of the first and second rows of buildings are high: 14 Pa and 4 Pa, respectively. PB (B) is a plane with six-point buildings in a staggered arrangement. The simulation results of PB (B) are similar to those of PB (A), but the second row of buildings is less affected by the first row, and there is a positive pressure area on the windward side of the second row of buildings.

PB (C) is a plane with six-point buildings in a half-enclosed arrangement. The distance between the two buildings in the first row is large, forming an opening. The layout of PB (C) divides six buildings into three rows. The windward wind velocity ratios of the first row to the third row are 0.32, 0.89, and 0.76, respectively. It is worth mentioning that the wind velocity ratios at the corner of the third row of buildings and the passage between the two buildings are high: 1.21 and 1.37, respectively. The front and back pressure differences of the buildings from the first row to the third row are 7 Pa, 5 Pa, and 10 Pa, respectively, and there is a large negative pressure area on the leeward side of the third row of buildings.

Table 3. The simulation results of point buildings.

Point Buildings	Wind Vector	Wind Pressure
PB (A)		
PB (B)		
PB (C)		
PB (D)		
PB (E)		

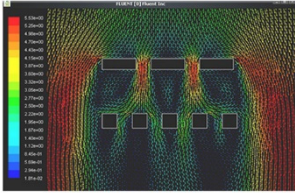
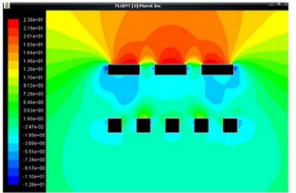
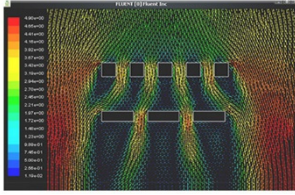
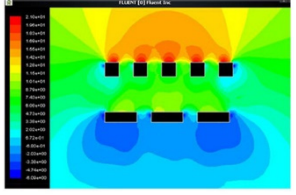
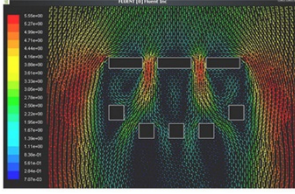
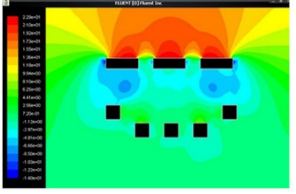
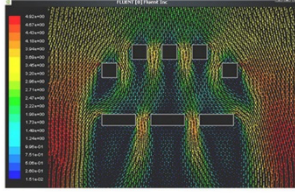
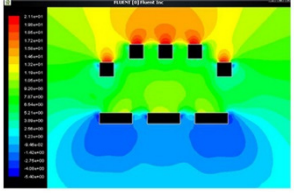
PB (D) is a plane with six-point buildings in a half-enclosed arrangement. The distance between the two buildings in the third row is large, forming an opening. The windward wind velocity ratios of the first row to the third row are 0.52, 0.72, and 0.60, respectively. The wind velocity at the passage between the buildings from the first row is relatively high, where it can reach 1.60. The front and back pressure differences of the buildings from the first row to the third row are 14 Pa, 10 Pa, and 6 Pa, respectively.

PB (E) is a plane with six-point buildings in an enclosed arrangement, forming a regular hexagon. The windward wind velocity ratios of the first row to the third row are 0.63, 0.72, and 0.84, respectively. The passage winds of the first row and third row of buildings are connected, and the wind velocity ratio is ~ 1.30 . The front and back pressure differences of the buildings of the first row and second row are 13 Pa and 10 Pa, respectively, and the third row of buildings is basically surrounded by a negative pressure area due to the influence of the buildings ahead.

4.3. Arrangement of the Slab-Point Combination Buildings

CB is used to represent slab-point combination buildings hereinafter. The wind vector and wind pressure results of CB (A), CB (B), CB (C), and CB (D) are shown in Table 4.

Table 4. The simulation results of slab-point combination buildings.

Slab-Point Combination Buildings	Wind Vector	Wind Pressure
CB (A)		
CB (B)		
CB (C)		
CB (D)		

CB (A) is a plane with point buildings to the south and slab buildings to the north, and the two rows of buildings have a parallel arrangement. The windward wind velocity ratios of the first and second rows of buildings are 0.48 and 1.01, respectively, and the wind velocity ratios at the channel between the sidewalls of the buildings are 1.84 and 1.14, respectively. The front and back pressure difference of the buildings of the first row is 20 Pa. The second row of buildings is mainly in a negative pressure area. A few places have positive pressure, which is affected by the passage wind between the sidewalls of the slab buildings ahead.

CB (B) is a plane with point buildings to the north and slab buildings to the south, and the two rows of buildings have a parallel arrangement. The windward wind velocity ratios of the first row of buildings are between 0.45 and 0.70, and the wind velocity ratios at the channel between the sidewalls of the first and second rows of buildings are 1.48 and 1.52, respectively. The front and back pressure differences of the buildings of the first and second rows are 15 Pa and 10 Pa, respectively.

CB (C) is a plane with point buildings to the north and slab buildings to the south, and the two rows of buildings have an enclosed arrangement. The windward wind velocity ratio of the first row of buildings is 0.46. The wind velocity increases at the corner of the buildings and the channel between the sidewalls of the buildings, and the wind velocity ratios are 1.66 and 1.85, respectively. Due to the influence of the slab buildings ahead, the wind velocity of the second row of buildings is decreased, and the wind velocity ratios at the corner of the buildings and the channel between the sidewalls of the buildings are both ~ 1.11 . The front and back pressure difference of the buildings of the first row is 20 Pa, and

it is much higher than that of the second row of buildings, which is mainly in a negative pressure area.

CB (D) is a plane with buildings in an enclosed arrangement, but the positions of its slab and point buildings are opposite to those of CB (C). The windward wind velocity ratio of the first row of buildings ranges between 0.33 and 0.82, and the wind velocity ratio at the corner of the buildings is 1.15. The wind velocity ratios at the channel between the sidewalls of the first and second rows of buildings are 1.38 and 1.33, respectively. The front and back pressure differences of the buildings of the first and second rows are 18 Pa and 10 Pa, respectively.

5. Discussion

5.1. Comparative Analysis of Three Kinds of Building Arrangement

SB (A), SB (B), and SB (C) represent different plane arrangements of slab buildings. According to the results of SB (A), the sudden increases in wind velocity at the passages make pedestrians feel uncomfortable. Although the wind velocity at the corners of buildings and the passages of their sidewalls in the SB (B) plane also increases, the airflow around the buildings in the whole site is generally smaller than that in the SB (A) plane. The wind environment of SB(C) is complex due to its enclosed arrangement, and the airflow velocity in the middle of the site fluctuates and is unstable. SB (C) is effective in resisting cold wind in winter, but it blocks outdoor natural ventilation in summer.

PB (A), PB (B), PB (C), PB (D), and PB (E) represent different plane arrangements of point buildings. In the PB (A) layout, the passages of the two rows of buildings are opposite, so strong wind runs through them, resulting in discomfort for pedestrians when walking through the area. Compared with PB (A), the ventilation condition of the PB (B) layout is better; however, the area of the second row of buildings affected by cold wind is increased, leading to a poor insulation effect in winter. PB (C) and PB (D) both have a half-enclosed arrangement, where the opening of the former plane faces north and that of the latter plane faces south. In the PB (C) layout, the cold wind from the north in winter can easily go deep into the downstream buildings, and the wind velocity in the central area of the plane is relatively high; also, the buildings ahead cannot prevent cold wind from affecting the second row of buildings. Conversely, the first row of buildings in the PB (D) plane can shield the second row of buildings from cold wind, which decreases the wind velocity of the central area. The wind condition of the PB (E) layout is complex in winter, and the absolute value of the wind velocity in the enclosed central area is wide.

CB (A), CB (B), CB (C), and CB (D) represent different plane arrangements of slab-point combination buildings. In the CB (A) layout, the slab buildings are located in a windward place, and the large size can prevent the cold wind coming from the north. There is a wide range of low-speed airflow areas on the leeward side, so the airflow ventilation in this area should be considered. Besides, it is not recommended to design garbage storages and underground garage vents in the leeward area to avoid the accumulation of pollutants. In the CB (B) layout, the incoming wind blows through the point buildings and is dispersed into multiple channel winds, resulting in a scattered wind velocity distribution in the leeward area, and the point buildings cannot block the cold wind for the downstream buildings. Moreover, it can be seen from the wind pressure results that the leeward side of the slab buildings is in a large negative pressure area and that the pressure difference between the windward and leeward sides is also relatively high, which is not conducive to wind protection in winter. The planes of CB (C) and CB (D) are similar to those of CB (A) and CB (B), respectively, but the CB (C) and CB (D) layouts both have an enclosed arrangement. In the CB (C) layout, the slab buildings also play a role in shielding the downstream buildings from cold wind. The arrangement mode of the half-enclosed point buildings increases the distance from the buildings ahead, the wind velocity of the central area is significantly attenuated, and the wind velocity of the downstream buildings is decreased compared with that of CB (A). In the CB (D) layout, the airflow distribution in the area between the two rows of buildings is scattered. There is a negative pressure area behind

the second row of buildings, which may create airflow vortices in many places, resulting in uncomfortable wind environments, which is unfavorable for pedestrian activities.

5.2. Implications of Designing Wind Environments for the Buildings of Shenyang

The wind environment design of residential areas in Shenyang is mainly based on wind protection in winter and ventilation in summer. Compared with SB (A) and SB (C), SB (B) is more suitable for the Shenyang area due to the following reasons. The first row of buildings has a preferable effect on resisting cold wind in winter, and the channel wind of the buildings ahead does not directly blow to the windward side of the second row of buildings. Besides, it offers multiple air outlets in summer, thus reducing the negative pressure area, which is conducive to guaranteeing ventilation in the site. It should be noted that due to the large wind pressure on the surface and corner of the windward buildings, heat preservation and wind resistance should be considered during the design process.

The above analysis of the plane with point buildings shows that the PB (D) layout is more suitable for the climatic conditions in Shenyang. In winter, the wind velocity decreases after passing through the first row of buildings, which makes the wind velocity distribution in the central area reasonable. In summer, the airflow in the site can be kept unblocked to prevent the influences of domestic garbage and other pollutant gases.

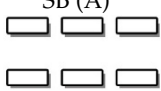
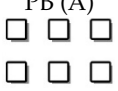
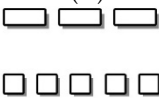
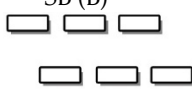
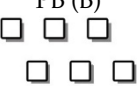
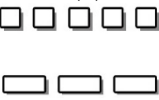
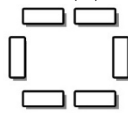
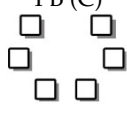
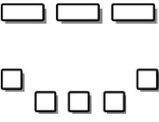
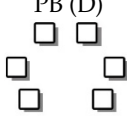
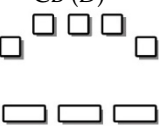
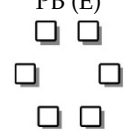
According to the discussion of different planes with slab-point combination buildings, the CB (A) and CB (C) layouts are both suitable for the climatic conditions in Shenyang. Both planes have slab buildings on the north and point buildings on the south. Thus, the cold wind in winter can be prevented by the slab buildings ahead, and the point buildings can be surrounded by a suitable wind velocity. The pressure difference between the windward and leeward sides is not too high, and the uncomfortable influence of cold wind in winter can be reduced.

Among the 12 kinds of layouts, SB (B), PB (D), CB (A), CB (C) can ensure favorable wind environments in the case of strong cold wind in winter in the Shenyang area (Table 5.). These layouts may also be suitable for cold areas such as Tieling and Anshan, whose weather conditions are similar to those of Shenyang.

5.3. Limitations

In this study, the winter wind environments of different kinds of residential buildings in Shenyang were simulated and analyzed. However, due to the high requirements for wind protection in winter in northern China, and because the outdoor wind environment in summer is not clearly defined in the architectural design requirements, the wind environments of the studied residential buildings in summer were not explored. Additionally, this study focused on the impacts of building arrangements on the wind environments of residential areas. However, many other factors, such as landscape facilities, green plants, and building surface pavements, can affect wind environments. Thus, these factors should be considered in future research to increase the accuracy of the simulation results.

Table 5. Overall results of the 12 kinds of layouts.

Arrangements	Results	Arrangements	Results	Arrangements	Results
SB (A) 	○	PB (A) 	○	CB (A) 	✓
SB (B) 	✓	PB (B) 	○	CB (B) 	○
SB (C) 	○	PB (C) 	○	CB (C) 	✓
		PB (D) 	✓	CB (D) 	○
		PB (E) 	○		

6. Conclusions

This study investigated and summarized the representative layouts of the residential areas in Shenyang. The wind environments of different architecture arrangements were also analyzed based on the CFD Fluent software. The wind environment design of the residential areas in Shenyang mainly focuses on wind protection in winter. Thus, the staggered layout of slab buildings is recommended because the buildings ahead can effectively prevent the penetration of cold air in winter. Additionally, it is a good choice for point buildings to adopt the half-enclosed arrangement with an opening to the south, where the wind velocity of the incoming flow in winter is weakened after passing through the first row of buildings, which makes the wind velocity distribution in the central area average and reasonable. When slab buildings and point buildings are combined, the arrangement of slab buildings on the north and point buildings on the south can create suitable wind conditions. In particular, the slab buildings ahead can effectively prevent the penetration of cold air in winter, so the point buildings can be in a suitable state with regard to wind velocity, and the pressure difference between the windward and leeward sides would not be too high. In this paper, three kinds of arrangement and combination forms suitable for the residential layouts in the Shenyang area are recommended, all of which can ensure favorable wind environments in the case of strong cold wind in winter. The study corresponds to the government policies and building codes of China and can help urban planners and policy makers in better understanding wind comfort at the pedestrian level in the Shenyang area. This study practically and theoretically contributes to the research on the wind environments in residential areas and provides useful guidance for architects and urban planners. Moreover, it provides new insights for further exploring how to improve wind environments in residential areas.

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