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Analysis of Urban Public Spaces' Wind Environment by Applying the CFD Simulation Method: a Case Study in Nanjing

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Abstract

The increase in the density of high-rise buildings is making urban air flow increasingly complex, and the wind environment conditions in urban public spaces are considerably changing. At present, few studies focus on the relationship between wind environment and the master plan of urban public spaces or attempt to improve the wind environment of public spaces from a landscape design perspective. To resolve this gap in information, this study explored the relationship among wind speed, seasonal comfort level in Nanjing, and different types of planting patterns. Computational fluid dynamics (CFD) software was used to quantify the seasonal wind environment of Xuanwumen Square in Nanjing. Three planting designs were created on the basis of the results, and their CFD results were compared among one another. Comparison results show that the second planting design provides the best wind environment, and its comfort levels are 2.26, 1.92, and 2.09 out of 5 in winter, summer, and total. Understanding of the relationship among different landscape designs and their impacts on wind environment supports designers in improving the wind environment of Xuanwumen Square in Nanjing. This study provides new insights into relating urban public space design with the quantitative research of wind environment in the future.

Keywords: CFD simulation; wind environment; urban public space; landscape quantitative analysis

Introduction

The increasing degree of urbanization has made the wind environment inside the city increasingly complex. This situation is caused not by the macro-level environmental changes but by the near-ground environmental changes, that is, the local climate and environment changes formed by the complexity of public space form. The specific characteristics are described as follows: the city is in a quiet and windless state all the year round, the atmospheric flow is difficult, the local high temperature anomaly is increasing, and the aggravation of fog and haze directly affects people's living standard (Feng & Chu, 2017). Previous studies on microclimate have determined outdoor environmental comfort by black-ball temperature, airflow velocity, and relative humidity of air (Chen & Yang, 2014; Zhang, 2012; Zuo & Chu, 2003). Among them, airflow velocity, that is, the wind environment, has the most direct and significant relationship with the spatial form, that is, the most easily changed by human regulation. The previous research method of wind environment is mainly based on field test. Domestic scholars have combined it with various influencing factors

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to study wind environment. Hong and Lin discussed the relationship between wind and plants by reducing the influence of winter wind speed in the field test of a residential area in Beijing (Hong &Lin, 2014). They found that the layout optimization and improvement of a green space has also been explored in the numerical simulation analysis of urban outdoor wind environment. Ke and Sang introduced the leaf surface index to simulate and test the windbreak effect of small forest belts on the basis of on the urban street valley model; this model can reasonably simulate the dynamic shelter effect of shelterbelts (Ke & Sang, 2007). On this basis, the wind environment of urban public spaces has attracted considerable attention.

Quantitative research emerges as the times require, and scholars at home and abroad have extensively used computational fluid dynamics (CFD). Dynamics (CFD simulation) method quantifies the wind environment of public spaces, such as parks, residential green areas, and squares. Li and Zhao used CFD technology to explore the relationship among residential building density, building height, windward area, and average wind speed in residential planning (Li & Zhao, 2010). Liu used CFD method to simulate the microclimate of the planned buildings, predict the impact of the planning scheme on the microclimate of buildings and blocks, and quantitatively analyze the impact of the planning scheme on the space to optimize the layout (Liu, 2005).

Under the background of rapid urbanization, improving the urban public space environment using wind environment and allocating plant landscape scientifically and effectively are important tasks. Therefore, this study examines the wind environment of a city square, which is a core area of urban public activities. Improvement of the wind environment through different plant barriers is explored through the analysis and evaluation of the existing wind environment conditions of the square in summer and winter. The environmental comfort levels using different planting strategies are also compared. Three schemes are suggested for improving Xuanwumen Square in Nanjing. This work provides a new idea for the quantitative study of urban public space wind environment in the future.

Site analysis

The total area of Xuanwumen Square in Nanjing City is 1.44 ha, and the square is close to Xuanwumen Station of Line 1 of Metro, Xuanwu Lake Park in the East and Nanjing City Center in the west. Xuanwumen Square, which is a public space of urban traffic hub, is surrounded by many large public buildings. The square is located near Xuanwu Lake Park, which is a large area of water. The high density of the city changes the air flow of the plot rapidly and complicates the wind environment conditions. Thus, the plot is located near Xuanwu Lake Park. Wind environment has high research value.

Nanjing belongs to the humid climate of subtropical region. Under the control of westerly circulation, the monsoon is remarkable, the seasonal phenomena change distinctly, the dominant wind direction is northeast and southwest, and the southeast wind is dominant in summer. Given the climate characteristics of cold winter and hot summer in subtropical monsoon climate zone, the dominant wind direction and the average wind speed downward of the dominant wind on summer solstice and winter solstice are selected as the parameters of wind environment simulation. The CSWD format meteorological data file provided by China Meteorological Data Network indicated that the dominant wind direction in summer is 20°SE, the average wind speed of 1.5 m pedestrian height is approximately 2 m/s, the main wind direction in winter is 70°NE, and the average wind speed at 1.5 m pedestrian height is 4 m/s, which is used as the wind environment simulation parameter (Xu & Han, 2018). On the basis of the latest topographic maps in ARCGIS and

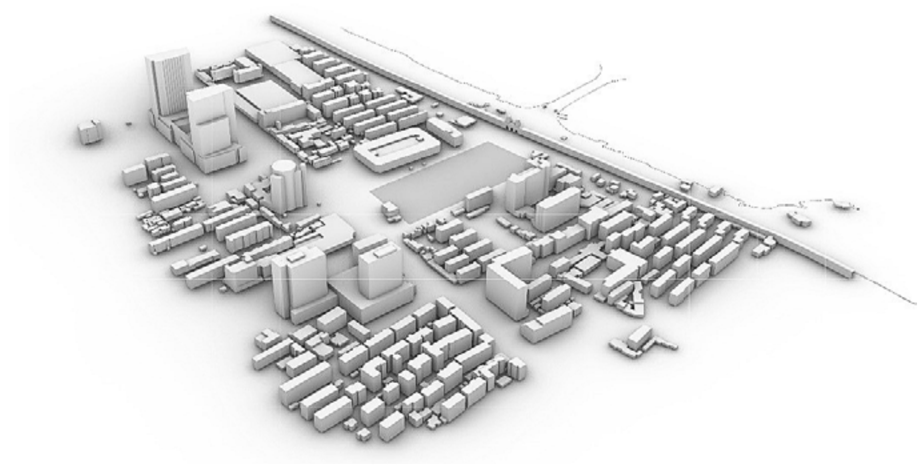

Figure 1. 3D model of Xuanwumen Square

many field investigations in March 19, Rhino software is used to build 3D models of site structures (such as city walls) and buildings (Fig. 1). As observed, the use of flat or sloping roof slightly affects the simulation results of this large-scale downwind environment. Thus, the sloping roof is simplified to flat roof. The red plot in the picture is Xuanwumen Square.

Computational Fluid Dynamics

CFD is a software used as a simulation tool. CFD has the advantages of low cost, good simulation conditions, good repeatability and easy control compared with observation and wind tunnel tests. The author mainly discusses the influence of wind speed on users of public space rather than the study of space fluids. Thus, the analysis is performed through a 2D cross-sectional view at 1.5 m. The evaluation method is based on CFD wind running results and wind environment comfort evaluation grade of Nanjing. The specific steps are discussed as follows:

The simulation uses a new generation of CFD simulation software called XFlow developed by Next Limit Technology to simulate wind speed. Compared with wind tunnel experiments and field measurements, XFlow simulation can predict wind conditions of different scales well. The analysis using XFlow has been recognized in Japan, China, and Korea. The non-network method in XFlow is based on particles and has a complete Lagrange function, which has great advantages over other CFD simulation software in the past.

Data and methods

1) The influencing factors of the square wind environment are analyzed. The ideal square wind environment has good ventilation and pollutant diffusion function in summer and the ability to resist the cold wind in winter. Accordingly, the wind environment in different seasons can provide better comfort. As shown in Table 1, the factors that influence the wind can be summarized as the following six aspects (Li et al., 2010). The transformation of space elements is the most possible and is thus mainly discussed in this paper.

Three factors are summarized in Table 2. Among them, plant barrier has the material form of enclosing and dividing urban square space, creating good square space form, effectively blocking, reasonably guiding, and properly reducing wind. This approach has relatively low cost, high environmental benefit, and good visual effect. Therefore, this study comprehensively analyzes plant-related strategies.

In the various forms of garden planting based on previous studies (Huang, 2016) and field observations, six typical models are selected for simulation experiments in the horizontal direction to observe the different planting forms around the impact of the wind environment. Necessary simplification of the plant model is applied in the experiment. The wind tunnel test conducted by GreenS showed that the tree shape is simplified in the wind tunnel test of each canopy shape (Greens, 1995; Liu & Si, 2018). The simplified shape is simple, conducive to calculation, and of excellent convergence compared with other models (Zhang, 2015). Accordingly, the current simulation experiment set a single plant to a long elliptical crown

Table 1. Factors of square wind comfort and their implementation phrases

Influencing factor	Implementation phase	Whether to adopt or not
Urban Road Layout	Urban Overall Planning and Reform	×
Blocks and Buildings	Phase of Urban Overall Planning and Reform	×
Surrounding Architectural Layout	Planning and Design Stage of New Buildings and Reconstruction Stage of Existing Buildings	×
Space Elements of Square	Design Stage of New Square and Reconstruction Stage of Existing Square	√
Functional Activity Layout	Design Stage of New Square and Reconstruction Stage of Existing Square	×
Substantive Elements of Square	Design Stage of New Square and Reconstruction Stage of Existing Square	×

Table 2. Factors of space elements of square

Influencing factor	Implementation phase	Whether to adopt or not
Terrain barrier	Tuqiu, Sunken Square	×
Plant barrier	Arrangement, clustering, etc.	√
Building and infrastructure Barrier	Windbreak fences (Ivana et al., 2017), sculpture, etc.	×

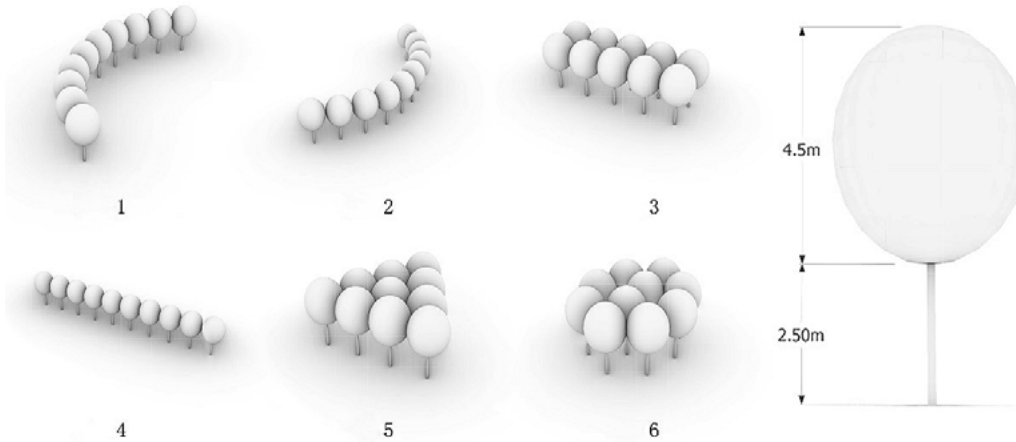

Figure 2. Planting patterns affecting wind environment

with a height of 7 m, a branch height of 2.5 m, a canopy height of 4.5 m, and a width of 3 m. The tree is at the center of the calculation area. Modeling with AutoCAD and exporting the stl format further reduce the error caused by the reversal of the front and back.

2) Wind environment rating is classified. In different cities, the wind environment can meet people's needs at different temperatures and humidity. The wind speed of body comfort differs. According to the relationship between temperature and humidity, the formula for calculating body comfort is:

$$SSD = (1.818 \cdot t + 18.18) \cdot (0.88 + 0.002 \cdot f) + (t - 32) / (45 - t) - 3.2V + 18.2, \quad [1]$$

where t is the temperature, f is the relative humidity, and V is the wind speed.

The climatic data in this study are based on the cumulative monthly mean temperature (°C) and wind speed (m/s) from 1982 to 2012 in Nanjing. With relative humidity (%), the data come from China Meteorological Science Data Sharing Service Network and have high reliability (Tang et al., 2014). In Nanjing, the average temperature from June to August is 26.9 °C and the average relative humidity is 78.4%. In December to February, the average temperature is 4.1 °C and the average relative humidity is 72.7%. On this basis, the human comfort index of Nanjing can be classified as follows:

Table 3. Summer wind environmental comfort level

Wind speed (m/s)	Summer ssd
5.44<V≤8.86	59–70
3.88<V≤5.13	71–75
2.63<V≤3.56	76–79
0.75<V≤2.31	80–85
V≤0.43	86–88

Table 4. Winter wind environmental comfort level

Wind speed (m/s)	Winter ssd
V≤0	59–70
V≤0	51–58
0<V≤1.50	39–50
1.81<V≤5.56	26–38
5.88<V	0–25

3) Colors are used to distinguish the active blocks of different wind speed levels in Xuanwumen Square for illustrating the problem intuitively based on the comfort level of winter and summer wind environment in Tables 1 and 2. The color and corresponding wind speed are shown in Table 3. Inspired by previous research (Zeng, 2019), the square is evenly partitioned using 50×20 fishnet grid in ArcGIS; then, the wind speed simulated by CFD is graded to fill in the corresponding color. A dark color corresponds to low comfort.

Table 5. Evaluation grade of wind environment comfort in Nanjing

Level of comfort	Summer wind speed (m/s)	Winter wind speed (m/s)	Color
Level 1 very suitable	5.44–8.86	0	
Level 2 suitable	3.88–5.13	0	
Level 3 normal	**2.63-3.56**	**0-1.50**	
Level 4 unsuitable	0.75–2.31	1.81–5.56	
Level 5 strongly inappropriate	0.00–0.43	5.88–∞	

Results and discussion

Wind Environment Assessment of Xuanwumen Square

After the significance of microclimate in urban public space is clarified and the effects of different planting forms on the microenvironment are explored, this study conducts an environmental simulation of Xuanwumen Square in Nanjing and analyzes the existing sites in the following sub regions to provide a quantitative theoretical basis.

In the previous model preparation, the object is a city square and the scope is large. Thus, the modeling reference standard of the Japan Institute of Architects is adopted, that is, buildings within the 1–2 ha area around the target building should be clearly modeled. CFD software is used to simulate the wind environment evaluation of Xuanwumen Square in the surrounding environment, and at least one block model is extended in each direction outside the area. Technically, 3D modeling of buildings, structures (such as city walls), and major terrain is performed in conjunction with field research in AutoCAD and Rhino software.

In the calculation setting, the wind environment model still adopts the 3D kernel mode, and the calculation method adopts the external flow calculation. The resolution is controlled within 0.5 m to ensure the accuracy of the results. At the end of the calculation, the 2D image interception at a height of 1.5 m is performed in the post-processing section. The reason is that the wind environment at the height of 1.5 m is closest to the pedestrian height. Accordingly, the impact on residents is most evident.

In analyzing wind speed, this study selects the average wind speed as described above, that is, the winter solstice is 4 m/s, the wind is upward, and the dominant wind direction in winter is north to east. After CFD simulation, the impact of the surrounding environment of Xuanwumen Square on the wind environment of the research block is obtained as follows:

In the winter in Nanjing, the too high wind speed causes discomfort. Figure 4 shows the winter wind environment in the activity areas.

The wind speed is studied at 2 m/s in the previous summer solstice, and the dominant wind direction in the summer is southeast to south. The summer impact of the surrounding environment of Xuanwumen Square on the study of the wind environment of the plot is obtained as follows on Fig. 5.

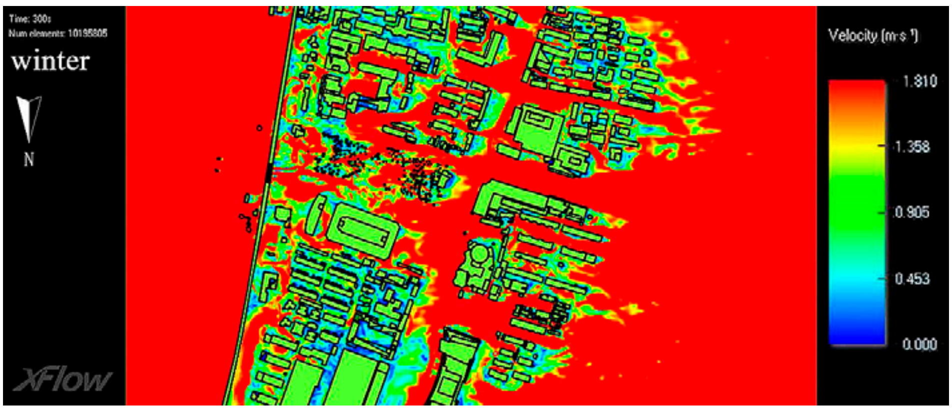

Figure 3. Current wind environment of Xuanwumen Square in winter

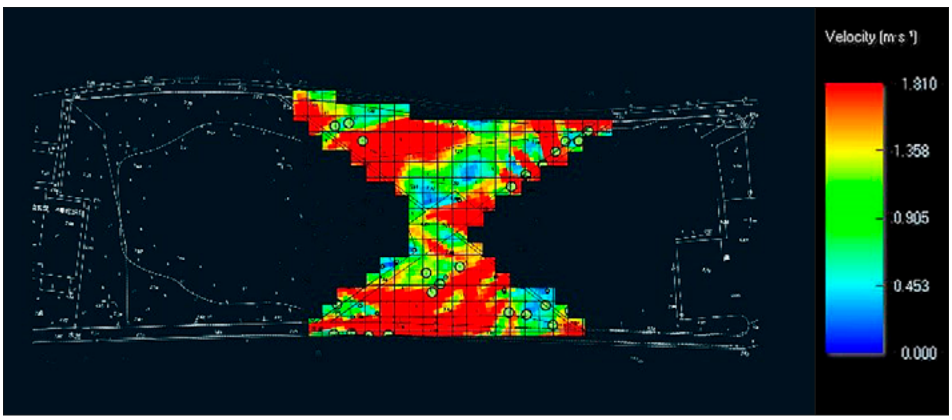

Figure 4. Winter wind environment in resting and walking areas

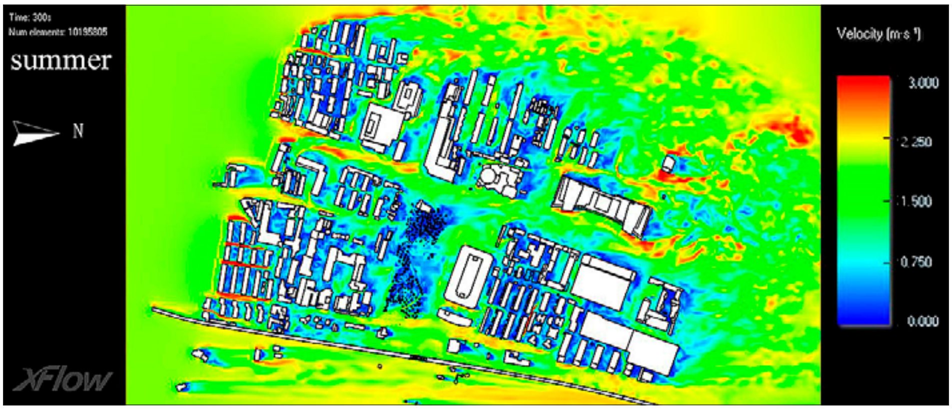

Figure 5. Wind environment of Xuanwumen Square in summer

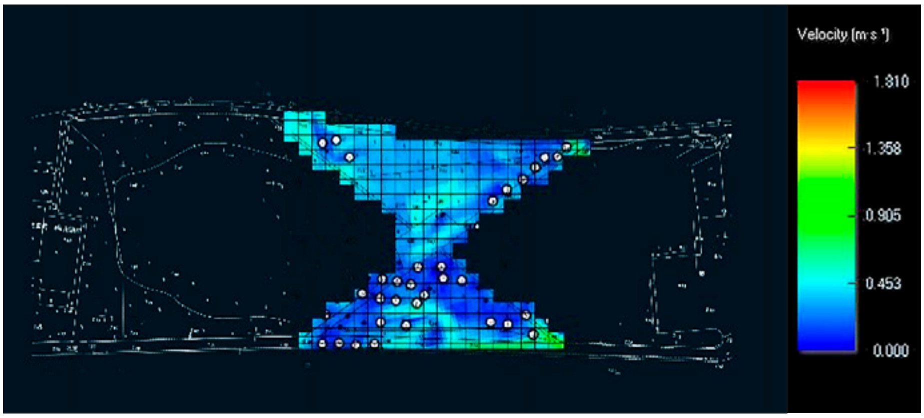

Figure 6. Summer wind environment in resting and walking areas

In the summer of Nanjing, the too low wind speed does not easily flow out, the pollutants are not easy to spread, and the human body feels comfortable.

Plant barrier mode assessment

Garden plants are planted in various forms, each of which has different effects on the wind environment. This work studies six different types to determine the influence of plant communities in planting forms on the surrounding wind environment. The height of the tree simulated in this study is 7 m. The height of the branches is set to 2.5 m, the height of the canopy is set to 4.5 m, and the width is set to 3 m. The analysis method of wind environment model in 3D kernel mode uses the outflow algorithm. For accurate imagery, the resolution is controlled to 0.5 m. The calculus ends in the post-processing section at a height of 1.5 m. The wind environment at 1.5 m height is closest to the pedestrian height. Thus, its impact on residents is the most evident. This study selects the average wind speed of the winter solstice mentioned above and uses 4 m/s as the parameter for wind speed studies. The wind speed of the plant barrier running wind in Figure 7 is 0–5 ra/s. Accordingly, all the results in Figure 12 use the same legend. The 300 s CFD simulation is conducted to ensure the accuracy of the results. The impact of six different plant barriers on the wind environment is obtained as follows in Fig. 7.

The figure above shows that combination A is a straight line of planting. Within 0–20 m from the tree, the wind speed is the lowest and falls below 1.265 m/s, and the branch is highly uniform. In the range of 20–40 m, the average wind speed is approximately 2.5 m/s, and the wind speed is beyond 40 m. The range wind speed gradually increases. The sectional view reveals that the wind speed has increased to a certain extent vertically above the trees, and the higher area is less affected than the lower area.

In combination B, the two rows of straight-line crops formed in the downwind area have a very low wind speed. The wind shadow range is smaller than that of one row of straight-line crops, and the distribution is relatively concentrated. The average wind speed is 0.02 m/s. The area affected in the vertical direction of the facade should be larger than one line of straight planting. Therefore, increasing the number of planting rows can effectively reduce wind speed. On the basis of combinations A and B, scheme 1 is created and assessed as follows in Fig. 8.

The arc-shaped planting form of combination C can have the largest range of influence in the upwind direction, but the wind field characteristics under the trees are highly complicated. The gap between each

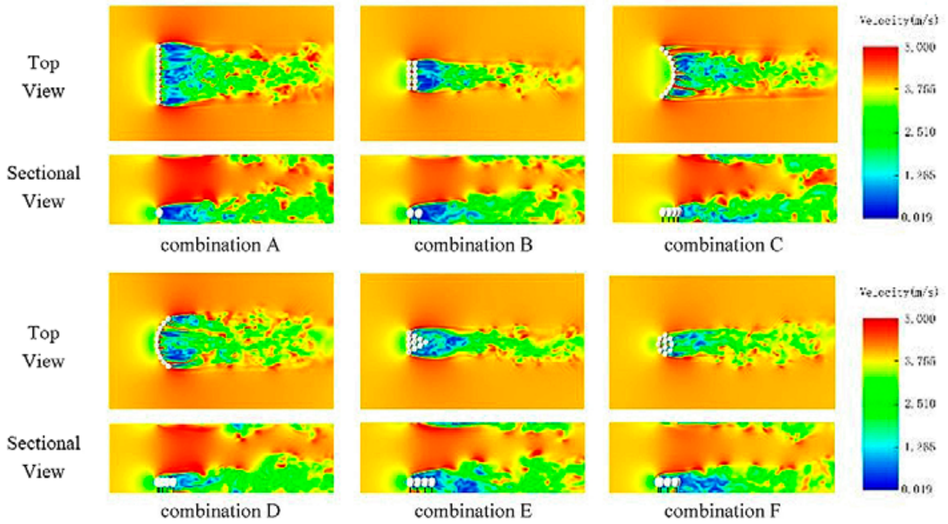

Figure 7. Plant barrier mode assessment

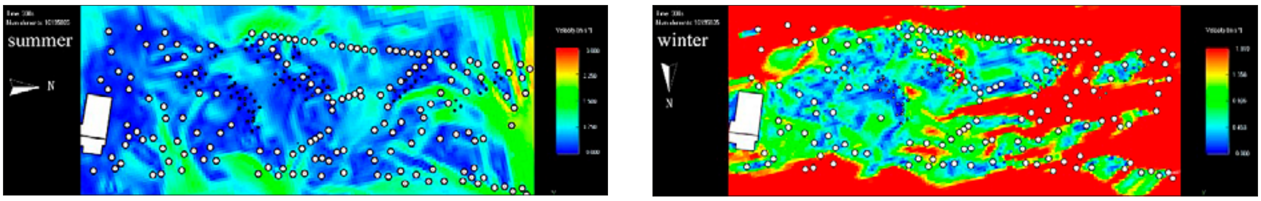

Figure 8. Summer (left) and winter (right) results of scheme 1

tree forms a high wind speed region with a length of 5–10 m and reaches 5 m/s. The arc-shaped planting of combination D also causes a narrow and high wind speed area in the gap between the trees on both sides of the tree. Accordingly, nearly 50% of the wind shadow area forms within 20 m of the leeward area. The two arc-shaped plantings form the smallest wind shadow area on the profile, the wind speed attenuation is not evident, and the wind blocking effect is worse than that of the row planting trees. On the basis of combinations C and D, scheme 2 is created and assessed as follows in Fig. 9.

Combinations E and F are triangular and circular dense plants, respectively. The incoming wind has a similar attenuation trend in the leeward area of the trees, but the effects are not as significant as the row planting. Triangular dense planting forms a calm wind area within 30 m from the tree, and the area where the wind speed drops below 1.265 m/s exceeds 50%. Among them, a clear wind shadow area is formed within the range of 20–30 m from the tree, and the wind speed is as low as 0.02 m/s. On the basis of combinations E and F, scheme 3 is created and assessed as follows in Fig. 10.

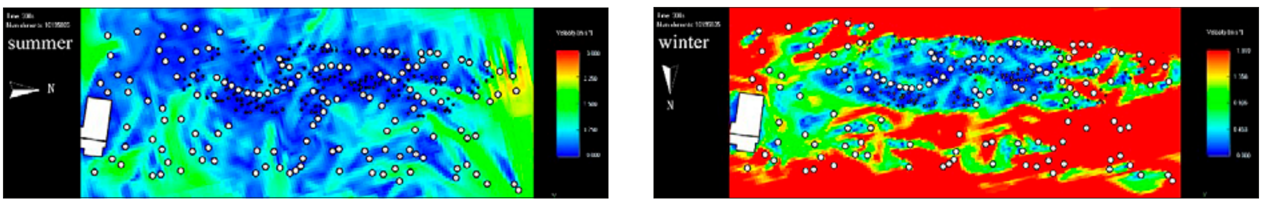

Figure 9. Summer (left) and winter (right) results of scheme 2

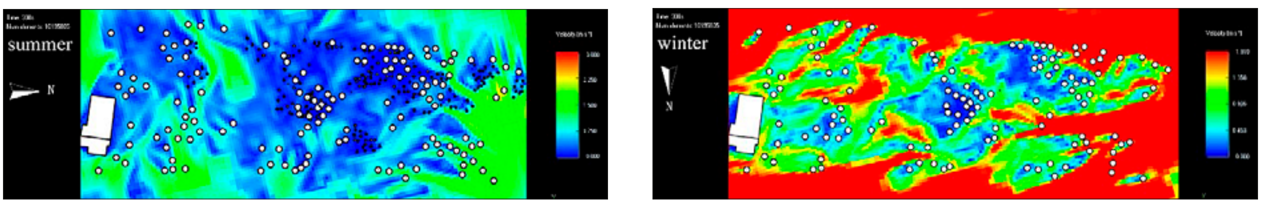

Figure 10. Summer (left) and winter (right) results of scheme 3

Comfort level of wind environment Assessment

On the basis of the body comfort level of wind environment in Tables 1 and 2 above, this study uses 50×20 fishnet grid in ArcGIS to partition the square evenly and distinguish the blocks of different wind speed levels simulated in CFD by filling in the corresponding color of the comfort level. The two situations of winter and summer are overlaid to analyze the total comfort level for illustrating the results intuitively. A activity side and on the active lawn. The windshield effect is considered highly significant. The average comfort level in scheme 2 is the highest among the three at 1.92 out of 5. In scheme 3, triangular and spherical densely planted evergreen trees can only reduce the wind speed in a short distance from the downwind direction. The wind shadow area formed is smaller than those in the two other schemes, and the average comfort is lower at 1.82 out of 5.

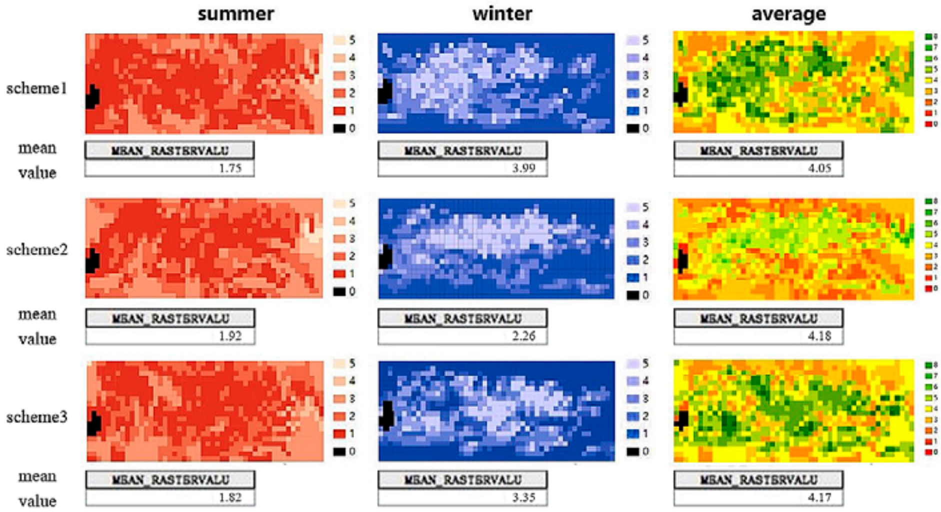

Figure 11. Comfort levels of schemes 1, 2, and 3

dark color indicates low comfort. The existing square consists of a central rest point. Overlaying the existing site plan show that the overall wind speed is high due to lack of building shelter on the northeast side in winter. Meanwhile, the air flow is blocked by dense forests in summer, thereby causing low body comfort.

In scheme 1, a linear line of evergreen trees on the north side of the activity area forms a windbreak to effectively reduce the winter wind speed, and a wind shadow area is formed in the activity space. In scheme 2, evergreen trees are planted in a straight line on the

In summer, the southeast wind is blocked by the building on the south side. As a result, a wind shadow area and a turbulent area are formed on the square. The activity place fails to meet the comfort needs of people when they are conducting outdoor recreation activities. Three solutions are implemented on the south side to improve the aforementioned situation. Trees are evacuated and planted in the activity area, and ventilation channels are reserved for the activity space in summer. Among them, schemes 1 and 3 can achieve high average comfort levels of 3.99 and 2.35, respectively.

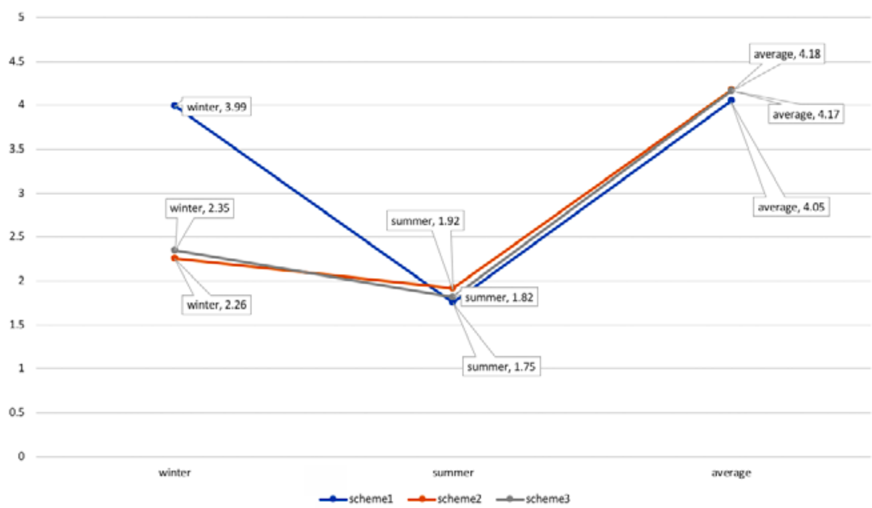

Figure 12. Comfort levels of schemes 1, 2, and 3

Conclusions

This study compares and identifies the impacts of different tree-planting strategies and summarizes suggestions for landscape design to improve the wind environment in public spaces. The results of this study led to the conclusions.

(1) The effects of six different tree-planting combinations were calculated and compared based on CFD numerical simulation results. Planting trees of combination A and B in the public space can achieve the lowest average wind velocity leeward on winter days, while the combination E and F result in higher wind velocity, especially within the down-wind part of the trees, when compared with the other tree-planting combinations. The maximum length of leeward area is 20m in combination A, while the minimum is less than 10m in combination F. Furthermore, the combinations C and D break the wind less effectively than A and B but have better ventilation in summer. The wind flow changes significantly with planted trees for different combinations.

(2) Three different planting schemes for the wind environment of Xuanwumen square were simulated. Accordingly, the body comfort level in different situations were calculated and analyzed. Scheme 2 scores the highest average comfort level in winter and summer, which is 4.18 out of 5. However, the results revealed that the comfort level of scheme 2 scores the lowest winter when compared with other schemes. Thus the solution needs to balances the comfort of the wind environment in their time domains to optimize the public space environment.

These findings are beneficial for designing a comfortable environment in the hot-summer and cold-winter public space. Further studies should be carried out to focus on more detailed analysis of shape, branch height, combination with shrubs and herbs, in order to investigate in detail the effect of the tree planting forms for the outdoor comfort.

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