Abstract
The study explores the influence of six parameters on natural ventilation of stacked sports buildings, using parametric modeling and CFD numerical simulation. The parameters examined are the number of inlets (P1), the width of inlet (P2), the sill height (P3), the height of inlet (P4), the number of cavities (P5), and the height of the air outlet (P6). The results show that with the increase of P1 and P2, the wind speed of reference plane continues increasing, and the uniformity of flow field is improved. With the increase of P3, the wind speed continues declining initially, and the wind speed remains stable later. With the increase of P4, the wind speed continues increasing, and when the air flow reaches deeper part, the uniformity is not significantly improved. With the increase of P5, the wind speed continuously increases initially and then decreases. With the increase of P6, the wind speed increases overall. The results are expected to provide guidance for designing natural ventilation of stacked sports buildings.

Highlights
- Taking stacked sports buildings as the research object
- Constructing a continuous path of airflow movement through implantation of cavities
- Exploring the influence of parameters combining parametric modeling and CFD numerical simulation

Introduction
In recent 10 years, the urban sports buildings in China tend to be designed in a vertically stacked style, to meet the rapidly developed diversified sports demands (Jin, 2012; Xie, 2014; Yao and Qian, 2019; Bai et al, 2020). The stacked style is mostly used in sports buildings for daily training and fitness, such as public fitness centers, training halls, university gymnasiums and other public multi-functional sports facilities. Compared with competitive gymnasiums for professional athletes, the main users of stacked sports buildings are the general fitness crowd (Zhou, 2012). And the building usually contains multiple large sports halls without large-scale seating areas, to emphasize the participation of the masses, and weaken the performance function of the building (Guo, 2016).

In cold regions, the space layout of the stacked sports buildings is particularly compact to cope with extreme weather conditions (Zhang et al, 2019). For example, large space and ancillary space (i.e. toilets, changing rooms, equipment rooms and other service facilities) are combined in a three-dimensional manner. Intensive space keeps the overall building with small shape coefficient, effectively reducing heating energy consumption in winter (Liu et al, 2020). However, the compact layout of the space also leads to the difficulty for natural ventilation, which causes the rising energy consumption of the air-conditioning system, and thus is not conducive to the low-cost operation of the stacked sports buildings (Bai et al, 2020).

The spatial shape parameters of sports buildings have a significant impact on natural ventilation. Through CFD numerical simulation, Li (2013) found that the asymmetric roof shape of sports buildings, especially the asymmetric overhang shape, significantly increased the wind speed and air exchange rate. And the direction and position of the roof edge and the smoothness of the curved surface causes the differences in the negative pressure of the roof, affecting the natural ventilation effect (Xie, 2012). The side interfaces of gymnasium buildings can be divided into three types: outward, vertical and inward (Lv, 2011). Li (2014) showed that the inclined interface can increase the wind pressure difference, and the inward interface had better performance than the outward interface on natural ventilation.

With vents connecting the internal and external environments, ventilation can be enhanced by reasonably setting vents. For example, the top ventilation windows and the bottom rotary doors are used in Kumamoto Park Dome in Japan to enhance natural ventilation (Fan, 2001). In this case, the air exchange effect was improved by reasonably setting the angles and air inlet directions of the four rotary doors to create the cyclonic airflow in the field under the action of heat pressure and wind pressure. Rajagopalan (2013) simulated six different air inlet and outlet layout schemes in a mixed ventilation gymnasium in Australia and suggested the best opening strategy, after comparing and analyzing the ventilation efficiency and comfort of these schemes (Rajagopalan and Luther, 2013). Zhao (2014) carried out CFD simulation on the side window combinations at 7 different positions in a gymnasium building. Through comparing the thermal comfort and air quality of the combinations, it was found that the upper and lower ventilation windows on the two sides were the best combination, due to the height difference.
In addition to the research on combination mode of the air inlet and outlet, there are also studies on the opening and closing states, shape, size and other parameters (Van Hooff and Blocken, 2010; Cao, 2015). Qian (2018) discussed the impact of sliding retractable roofs on natural ventilation in gymnasium. The results showed that the opening and closing states had a significant impact on the indoor thermal comfort. For when the roof was opened, the indoor temperature decreased by about 2 °C. Cheng (2020) took the square gymnasium as the research object, and used CFD numerical simulation method to compare the effects of three vent shapes on the wind pressure ventilation. It was found that the vertical rectangular vent can increase the air intake and wind speed, and reduce the attenuation of airflow.

The research on natural ventilation in sports buildings has focused on the space shape and interface vent, mainly using simulation, measurement. However, the research objects are mostly the single large space of the gymnasium. And few studies were conducted on the natural ventilation of stacked sports buildings. Due to the complexity of the space combination of the stacked sports buildings, it is difficult to achieve the overall natural ventilation only through the ventilation openings or space forms. In the current study, the ventilation cavity was implanted, taking advantage of the spatial layout characteristics of stacked sports buildings, and the path for the continuous airflow movement was constructed using the synergistic effect of the interface vents and the cavity. Parametric modeling and CFD numerical simulation were used to investigate the influence of vents and cavity parameters on the natural ventilation performance.

Typical model
Spatial hierarchy
The data of 12 stacked sports buildings in 6 cities in cold regions of China (i.e. Beijing, Tianjin, Changchun, Shenyang, Dalian and Lanzhou) were collected (Figure 1). It can be seen that a stacked sports building usually contains multiple large space sports halls, with a compact and flexible spatial layout.

![Figure 1: Plans of 12 stacked sports buildings in 6 cities in cold regions of China.](image)

As shown, the 12 buildings adopt the spatial hierarchical structure in designing, although they are in different shapes. In these designs, an independent functional group with large space as the core is formed by setting several auxiliary spaces around one large space sports hall; then several independent functional groups around one public space are integrated forming the whole building. The whole building presents a three-level spatial structure: the whole building, functional group, and sport space. And the level of functional group is the core. The current study focuses on the airflow movement of large space within the functional group. And since the air flow between different functional groups is weak, it was ignored. Using the data collected from the 12 buildings, one typical functional group of stacked sports buildings was extracted to establish the spatial model presented in Section 2.2.

Spatial model
As shown in Figure 2, in the vertical dimension, two large spaces without columns are stacked up, which is a typical spatial feature of stacked sports buildings. In the horizontal dimension, the auxiliary space is arranged along the long side of the large space. Therefore, it can be seen that the obstruction of the airflow in the sports hall is the main reason for the difficulty in natural ventilation. The plane size of the large space sports hall is 40m × 60m, to meet various sports function requirements. The floor height of the sports hall is 12m, to meet the height requirements of various fitness activities.

![Figure 2: Spatial model.](image)

Cavity implantation
In the functional group, the upper large space can be ventilated with the the roof skylight. Compared with the upper large space, however, the natural ventilation is more difficult for the large space at the bottom. Consequently, cavities need to be implanted to build a path for continuous airflow movement. Therefore, the current study only focuses on the natural ventilation of the sports hall in the large space on the ground floor, exploring the mechanism of geometric parameters on natural ventilation under the synergistic effect of vents and cavities. As shown (Figure 3), in various cavity layout modes, the surrounding cavity can ensure the integrity of the large space, facilitating the multi-functional conversion of the sports field, and the cavity distribution along the long side can ensure the shortest air flow path.

![Figure 3: Spatial model of implant cavity.](image)
Method

Parametric modeling

In function expressions, the coupling relationship and constraint relationship between geometric parameters were set. In the parametric model, the automatic establishment of the model was realized by inputting parameters, and the CFD simulation program was called for batch calculation without manually repeated operation.

The vent parameters include: the number of inlets, the width of inlet, the sill height, and the height of inlet. The shapes and positions of inlets on the facade were realized through changing and combining the four basic parameters. The positioning of inlets was simplified into a uniform distribution mode, (that is, the inlet spacing between adjacent inlets is equal) to form a uniform distribution of the flow field in the sports field. P1 is the number of inlets, P2 is the width of inlet, P3 is the sill height, P4 is the height of inlet, P7 is the distance between inlets, and P8 is the distance between the outermost inlet and the edge of the exterior wall. P1, P2, P3 and P4 are independent variables, and P7 and P8 are dependent variables (Figure 4).

Figure 4. Elevation diagram of inlet parameters.

P7 and P8 are used to control the uniform distribution of vents on the facade, and their values are set equal. The functional relationship among P1, P2, P7 and P8 is shown in Eq. 1 and Eq. 2:

\[ 2P_7 + P_1 P_2 + (P_1 - 1)P_7 = 60 \]  
\[ P_7 = P_8 \]  (2)

P7 and P8 can be expressed by P1 and P2, as shown in Eq. 3:

\[ P_7 = P_8 = \frac{60 - P_1 P_2}{P_1 + 1} \]  (3)

The constraint relationship between the parameters of the air inlet is as shown in Eq. 4 and Eq. 5:

\[ P_1 P_2 < 60 \]  (4)
\[ P_3 + P_4 < 12 \]  (5)

The plane size of the cavity need to be strictly controlled to reduce the impact on the size of sports space. The cavity plane is simplified to a square. The side length was set as a constant of 2m. The height of the cavity is set as 27m to avoid the impact of height on the architectural appearance caused. The number of cavities and the height of air outlet are set as independent variables to explore the effects of these parameters on natural ventilation.

P5 is the number of cavities. The cavities are set to be evenly distributed along the long side of the large space, and the spacing between adjacent cavities is equal. P9 is defined as the spacing between cavities, and P10 is the distance between the outermost cavity and the edge of external walls (Figure 5).

Figure 5. Profile diagram of cavity parameters.

P9 and P10 are used to control the uniform distribution of the cavity along the long side of the sports hall, and their values are set equal. The functional relationship between P5, P9 and P10 is shown in Eq. 6 and Eq. 7:

\[ 2P_{10} + 2P_5 + (P_5 - 1)P_9 = 60 \]  
\[ P_9 = P_{10} \]  (7)

P9 and P10 can be expressed with P5, as shown in Formula 8:

\[ P_9 = P_{10} = \frac{60 - 2P_5}{P_5 + 1} \]  (8)

The number of air outlets of the cavity is the same as that of the cavities, and the width of air outlets is 2m as the side length of the cavity. P6 is the height of the air outlet, as an independent variable, and its value is calculated from the top of the cavity downwards (Figure 6).

Figure 6. Section diagram of cavity air outlet parameters.

The constraint relationship between the parameters of the cavity is set as shown in Eq. 9 and Eq. 10:

\[ 2P_6 < 60 \]  (9)
\[ P_6 < 3 \]  (10)

The range of the number of inlets (P1) is set as 4-30, and the range of the width of inlet (P2) is set as 1-10m. Considering the effect of glare, the sill height is generally not less than 2m, and the range of the sill height (P3) is set as 2-10m. The range of the height of inlet is 1-10m.

CFD numerical simulation

The CFD numerical simulation method was used to simulate the natural ventilation of the sports hall at the bottom of the stacked sports building. The software ANSYS Fluent 2019 R1 was used. In running the CFD numerical simulation, the natural ventilation under the combined action of wind pressure and thermal pressure was comprehensively considered. The calculated domain size was set as follows (Figure 7).
The velocity inlet was set as inlet boundary of the calculation domain; the wind speed was set as the exponential wind speed profile; the wind direction was vertical to the elevation of the air inlet. The pressure outflow boundary was set as the outlet of calculation domain. The average wind speed of 3.1 m/s in transition season of a typical cold city, Shenyang, China, was used as the reference wind speed at 10m above the ground (Sun et al, 2013). As the stacked sports buildings are mostly located in urban areas with high building density in China, the ground roughness index is 0.22 (Bai et al, 2020). The calculation formula of inlet gradient wind speed is shown in Eq. 11:

$$U(y) = 3.1 \left( \frac{V_{0.5}}{10} \right)^{0.22}$$

Where, $U(y)$ denotes wind speed at height $y$ (m/s); $y$ denotes height (m).

Based on the measured results of Bai et al. (Bai et al, 2020), the inlet wind speed temperature, the building inner wall temperature and the cavity inner wall temperature were simplified and set as constants 22 °C, 28 °C and 30 °C, respectively. The air was set as incompressible ideal gas to simulate the change of air density with temperature. And the influence of gravity was also considered. Van Hooft T (2010) and Cheng (2017) confirmed that Realizable k-ε Model had best convergence and calculation accuracy in calculating natural ventilation of large space buildings. Therefore, Realizable k-ε Model is selected as the turbulence model for CFD simulation.

The 150 measuring points were evenly arranged in the 1.5m reference plane in the activity area. The average value of wind speed at the measuring points $V_{\text{Ave,Plane1.5}}$ was taken as the evaluation index. The calculation formula is:

$$V_{\text{Ave,Plane1.5}} = \frac{1}{150} \sum_{i=1}^{150} v_i$$

Where, $v_i$ is the wind speed value of the measuring point $i$; $V_{\text{ave}}$ is the average wind speed of 150 measuring points.

To ensure the calculation accuracy and efficiency, the hexahedral grid elements were used to mesh the computational domain. The grids were gradually densified from the external computing domain, to the transition region, then to the building, finally to the cavity (Figure 8). To check whether the grid size was fine enough, the grid sizes representing three fine degrees were used for independent verification. The size and total number of grids are shown in Table 1. Under the same simulation settings, used for calculation were three types of grids: rough grid, medium grid, fine grid. The 5 average wind speeds ($V_0.5$, $V_1.5$, $V_2.5$, $V_3.5$, $V_4.5$) of 5 reference planes (0.5m, 1.5m, 2.5m, 3.5m and 4.5m), respectively, were extracted for comparison (Table 2). It was found that the wind speed difference between medium grid and rough grid was relatively large, and the maximum error was 0.130 m/s. The wind speeds of medium grid and fine grid were very close in value, and the maximum error was only 0.041 m/s. The results showed that the calculation results would not significantly change, even if the grid was finer, and the medium grid met the requirements of calculation accuracy.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cavity</th>
<th>Building</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>0.3m</td>
<td>0.4m</td>
<td>0.8m</td>
<td>1.6m</td>
<td>5388153</td>
</tr>
<tr>
<td>Medium</td>
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<td>0.5m</td>
<td>1m</td>
<td>2m</td>
<td>2726294</td>
</tr>
<tr>
<td>Rough</td>
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<td>0.6m</td>
<td>1.2m</td>
<td>2.4m</td>
<td>1623201</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Simulations</th>
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</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2</td>
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<tr>
<td>1</td>
<td>4-20</td>
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<tr>
<td>2</td>
<td>6</td>
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<td>3</td>
<td>6</td>
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<td>4</td>
<td>10</td>
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<td>5</td>
<td>10</td>
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<td>6</td>
<td>10</td>
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**Table 2.** Wind speeds of each reference plane under three grid sizes.

**Control variable experiment**

The control variable grouping experiment was used to explore the influence trend and action law of a single geometric parameter on natural ventilation performance when it changed in a local range. In the experiment, each geometric parameter kept changing within its range of values, and other parameters remained unchanged. The experimental grouping is shown in Table 3.
Results and Discussion

The number of inlets

The influence of the number of inlets on the indoor flow field was explored. The numbers of inlets are 4 to 20, with an increment of 1. A total of 17 CFD simulations were performed. The contours of reference plane and section were extracted, as shown in Table 4.

As the plane contour shows, the overall wind speed continued increasing, with the increase of the number of inlets. The area with high wind speed expanded from four "narrow and long areas" to the whole reference plane, and the flow field distribution tended to be uniform. And the section shows that the outdoor air flow moved downward after entering the room. This is because the temperature of outdoor air was lower than that of the indoor air, and the density of the outdoor air was higher than that of the indoor air. Then, the airflow flew through the activity area for the sports personnel and afterwards moved to the depth. Finally, part of the air flow entered the cavities and part of it reversely returned to the air inlet, forming a "vortex". The increase of the number of inlets caused the gradual increase in wind speed in the activity area for sports personnel and inside the cavities, thus leading to an obvious wind pulling effect of cavities.

Table 4. The contours of reference plane and section with the number of inlet as a variable.

<table>
<thead>
<tr>
<th>Plan</th>
<th>P2=3</th>
<th>P2=5</th>
<th>P2=7</th>
<th>P2=9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section</td>
<td></td>
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</table>

The influence of P1 on natural ventilation is shown in Figure 9. With the increase of P1, the average wind speed fluctuated locally, showing an obvious upward trend as a whole.

![Figure 9. Influence of the number of inlets on the average wind speed.](image)

The increase of the number of inlets caused the increase of the total area of air inlets, which increased the intake volume of indoor air, thus leading to the increase of the reference plane wind speed. The increase of the number of inlets caused the air flow entering the room in a more dispersed manner in the horizontal direction, which significantly improved the uniformity of the reference plane flow field. The results are consistent with the simulation results of the natural ventilation of the side windows of the small non-seating gymnasium (Zhao, 2014). In this study, the increase in the number of side windows increased the indoor wind speed, and expanded the airflow influence area.

The width of inlet

The influence of the width of inlet on the indoor flow field was explored. The widths of inlets are 1 to 9m, with an increment of 1m. A total of 9 CFD simulations were performed. The contours of reference plane and section were extracted, as shown in Table 5. The plane contour shows that the overall wind speed continued increasing, with the increase of P2. At the initial stage, the area with high wind speed concentrated in the "narrow and long area", and then gradually expanded to the entire reference plane. And the section shows that the wind speed in the activity area for sports personnel increased, with the increase of P2.

Table 5. The contours of reference plane and section with the width of inlet as a variable.

<table>
<thead>
<tr>
<th>Plan</th>
<th>P1=5</th>
<th>P1=10</th>
<th>P1=15</th>
<th>P1=20</th>
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<tbody>
<tr>
<td>Section</td>
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</table>

The influence of P2 on natural ventilation is shown in Figure 10. At the initial stage, the average wind speed did not change significantly, with the increase of P2. When P2 exceeded 3m, the average wind speed continuously increased.

![Figure 10. Influence of the width of inlet on the average wind speed.](image)

The sill height

The influence of the sill height on the indoor flow field was explored. The sill heights are 2 to 10m, with an increment of 1m. A total of 9 CFD simulations were performed. The contours of reference plane and section were extracted, as shown in Table 6. The plane contour shows that the overall wind speed value continued decreasing, with the increase of P3, and the area with high wind speed gradually narrowed. And the section shows that the distance from the air flow to the depth gradually shortened, with the increase of P3. When the air inlet was at a lower position, the air flow quickly reached the activity area for sports personnel after entering, and then moved toward the deep areas. When the air inlet was at a high position, the air flow moved downward first after entering, and the wind speed decreased continuously.
during the descending process, resulting in the air flow accumulating in the air inlet area, which made it difficult to reach the deep part.

**Table 6. The contours of reference plane and section with the sill height as a variable.**

<table>
<thead>
<tr>
<th></th>
<th>P3=2</th>
<th>P3=4</th>
<th>P3=6</th>
<th>P3=8</th>
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</table>

The influence of P3 on natural ventilation is shown in Figure 11. At the initial stage, the average wind speed continued declining, with the increase of P3. When P3 exceeded 7m, the average wind speed was basically stable, indicating that when the sill height reached a certain level, the reference plane wind speed would not continue decreasing. The results are similar to those of Lv (2011) on natural ventilation in gymnasiums.

![Figure 11. Influence of the sill height on the average wind speed.](https://doi.org/10.26868/2522-2708.2023.1721)

**The height of inlet**

The influence of the height of inlets on the indoor flow field was explored. The heights of inlet were 1 to 9m, with an increment of 1m. A total of 9 CFD simulations were performed. The contours of reference plane and section were extracted, as shown in Table 7. The plane contour shows that the overall wind speed continued increasing, with the increase of P4. The area with high wind speed expanded to the whole reference plane. And the section shows that, with the increase of P4, the air inlet volume at the inlet increased, the wind speed in the activity area for sports personnel increased, and the air flow was more far-reaching.

**Table 7. The contours of reference plane and section with the height of inlet as a variable.**

<table>
<thead>
<tr>
<th></th>
<th>P4=2</th>
<th>P4=4</th>
<th>P4=6</th>
<th>P4=8</th>
</tr>
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</table>

The influence of P4 on natural ventilation is shown in Figure 12. With the increase of P4, the average wind speed shows an overall upward trend. The increase in the height of inlet caused the increase in the total area of the air inlet, which increased the intake volume of indoor air, thus leading to the increase of the reference plane wind speed. As the increase in height of inlet caused the increase of the air inlet area in the vertical direction, the air flow reached a deeper part, and the uniformity was not significantly improved. The result is similar to that of Cheng (2020) about the influence of the vertical-strip air inlet on the wind-pressure ventilation of the gymnasium. Compared with square inlet, the vertical-strip inlet increased the ventilation volume of the gymnasium by 6.82%, the average wind speed in the field area by 75%, and decreased the airflow attenuation in the depth direction.

![Figure 12. Influence of the height of inlet on the average wind speed.](https://doi.org/10.26868/2522-2708.2023.1721)

**The number of cavities**

The influence of the number of cavities on the indoor flow field was explored. The numbers of cavities are 1 to 12, with an increment of 1. A total of 11 CFD simulations were performed. The contours of reference plane and section were extracted, as shown in Table 8. The plane contour shows that the overall wind speed continued increasing, with the increase of P5. And the section shows that with the increase of P5, the wind speed in the activity area for sports personnel increased, and the wind speeds inside the cavities decreased gradually.

**Table 8. The contours of reference plane and section with the number of cavities as a variable.**

<table>
<thead>
<tr>
<th></th>
<th>P5=4</th>
<th>P5=6</th>
<th>P5=8</th>
<th>P5=10</th>
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The influence of P5 on natural ventilation is shown in Figure 13. With the increase of P5, the average wind speed went continuously upward. When the number of cavities exceeded 10, the average wind speed began to decline.

![Figure 13. Influence of the number of cavities on the average wind speed.](https://doi.org/10.26868/2522-2708.2023.1721)
With the increase of the number of cavities, the effect of thermal pressure on natural ventilation was enhanced, causing the average wind speed at the reference plane to increase. However, the number of cavities was not linear to the effect. When the number of cavity exceeded 10, the average wind speed on the reference plane went downward. The results are similar to those of Bai (2020) in simulating the natural ventilation in the National Fitness Center.

The height of outlet

The influence of the height of outlet on the indoor flow field was explored. The heights of the outlets are 0.6 to 3m, with an increment of 0.2m. A total of 13 CFD simulations were performed. The contours of reference plane and section were extracted, as shown in Table 9. The plane contour shows that the overall wind speed continued increasing, with the increase of P6. The area with high wind speed expanded to the whole reference plane. And the section shows that the wind speed in the activity area for sports personnel increased, with the increase of P6.

Table 9. The contours of reference plane and section with the height of outlet as a variable.

<table>
<thead>
<tr>
<th>P6=0.6</th>
<th>P6=1.4</th>
<th>P6=2.2</th>
<th>P6=3</th>
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<td>Plan</td>
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The influence of P6 on natural ventilation is shown in Figure 14. With the increase of P6, the average wind speed fluctuated locally, showing an obvious upward trend as a whole. As the height of outlet increased, the total area of the air outlet increased, which increased the driving force of natural ventilation, thus increasing the average wind speed of reference surface.

Figure 14. Influence of the height of outlet on the average wind speed.

Conclusions and Future Work

Using parametric modeling and CFD numerical simulation, the influence of geometric parameters on natural ventilation was explored. The results show that six geometric parameters had different effects on the average wind speed of the reference plane, the uniformity of the flow field and the wind speed at the depth.

With the increase of the number of inlets, the average wind speed of the reference plane continued increasing. The increase of the number of inlets made the air flow enter the room in a more dispersed manner in the horizontal direction, and the uniformity of the reference surface flow field was significantly improved.

With the increase of the width of inlet, the average wind speed of the reference plane did not change significantly at the initial stage. When the width of the inlet exceeded 3m, the average wind speed continued rising. The increase of the width of the inlet increased the area of the air inlet in the horizontal direction, which caused the increase of the wind speed of the reference plane and the flow field tended to be uniform.

With the increase of the sill height, the average wind speed of the reference plane at the initial stage continued declining. The distance for the air flow to the depth gradually shortened, leading to the air accumulating in the inlet area. When the sill height exceeded 7m, the average wind speed was basically stable and stopped decreasing. The increase in the sill height reduced the wind speed of the reference plane. Therefore, we suggest to increase the sill height in designing gymnasiums mainly for small ball sports with strict requirements for wind speed.

With the increase of the height of inlet, the overall wind speed continued increasing. As the height of inlet increased the air inlet area in the vertical direction, the air flow reached a deeper part, and the uniformity was not significantly improved.

With the increase of the number of cavities, the average wind speed at the initial stage continuously went upward. For the increase of the number of cavities and the enhancement of the effect of thermal pressure on natural ventilation increased the average wind speed of the reference plane. When the number of cavity exceeded 10, the average wind speed began to decline.

With the increase of the height of the air outlet, the average wind speed fluctuated locally, showing an obvious upward trend as a whole. The increase in the height of the air outlet increased the total area of the air outlet, thus reducing the flow resistance of the air outlet and promoting natural ventilation.

These results are expected to provide guidance for designing natural ventilation of stacked sports buildings. However, further research need to be conducted on the optimal combination scheme of these six geometric parameters examined in the current study, by introducing intelligent optimization algorithm and CFD numerical simulation program for coupling.

Acknowledgement

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