Research on Numerical Simulation and Energy Conservation Evaluation of Wind Energy Utilization in the Atrium

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Abstract: For the special building structure of tall atrium, the air distribution characteristics of atrium under natural ventilation were calculated by CFD numerical simulation method, and the energy-saving rate of natural ventilation was evaluated as well. By changing the area and position of outlet vents, the variation rules of temperature, PMV, ventilation efficiency and air changes under different combinations of vents were obtained. Besides, we estimated the energy-saving efficiency of natural ventilation during the transitional season by comparing with the previous studies. And the results showed that: the higher the position or the larger the area of the exhaust vents is, the higher the efficiency of wind energy utilization is, the more benefits we get to improve indoor thermal environment and air quality as well as human comfort. In the transition season, the combination of natural ventilation and air conditioning system is more conducive to energy saving than the whole air conditioning system, and the energy-saving rate can reach more than 62.9%.

1 INTRODUCTION

Natural ventilation is a quite important air conditioning technology. It helps reduce building energy consumption and solve the problem of indoor thermal environment and air quality. In natural ventilation system, thermal pressure and wind pressure promote ventilation of the atrium in a building. Natural ventilation is widely used in high-rise buildings. Due to the large and high atrium, the influence of solar radiation on ventilation is obvious, and compared with general small buildings, the indoor thermal environment of high-rise buildings has a greater instability.

Currently, the studies on the wind energy utilization of atrium building mainly focus on the following aspects: JK Yang (JK Yang, X Zhang, 2005) simulated the indoor temperature field of atrium with double-glazing curtain wall and obtained the best natural ventilation time under different indoor loads. Y Cheng (Y Cheng, YG Song, 2015) verified the feasibility of air conditioning system design in a practical case by simulating the temperature field and velocity field in the air-conditioned area of atrium in a mall during summer. HY Zhao (HY Zhao, CZ Meng, 2010) studied the the relationship between natural ventilation and window area as well as windows position in the tall atrium with doors closed and window opened, in order to study the best window size and location. By comparing the indoor thermal environment conditions of the upper side wall opening and the top opening of the large space building, X Wang (X Wang, C Huang, 2005) found that the opening at the top is more conducive to the improvement of the indoor thermal environment during the air-conditioning season.

Thus, researches on the ventilation effect of atrium by scholars are mostly confined to discussing the atrium structure in the form of a single outlet vent in the air conditioning season. For the combined exhaust outlet under natural ventilation, such as adopting the upper and lower exhaust ventilation at the same time, the effects of ventilation and energy-saving are not overstated. In this paper, by using the PHOENICS 2016 simulation software and the k-ε two-equation turbulence model, the atrium airflow characteristics of 12 different combinations of vents are calculated under the condition of half-open door in natural ventilation. The distribution of temperature, PMV, ventilation efficiency and ventilation frequency are also be

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analyzed to study the best wind energy utilization effect. At the same time, the energy-saving rate of natural ventilation in atrium in transition season is evaluated.

2 NUMERICAL SIMMULATION

2.1 Physical Model

Located in Zhuhai, Guangdong, the building is a children's playground with atrium, which covers an area of 31,900m^2 with a height of 41.82m and a total of two floors. The atrium belongs to the core atrium with length, width and height of about 132m×88m×41m. The second floor activity area is a circle of extensional walkways along the wall with an area of about 8583m^2. The center of the roof is an arched transparent glass with a radius of 40m and a net height of 5.85m, and the side of the glass is a membrane material sloping roof with an area of about 32,200m^2. The forms of vents are the circular vents at the top and the side vents at the junction of glass and membrane material roof, respectively. Fig. 1 and 2 is a plan and section view of the building, and Fig. 3 is a simplified building model for simulation.

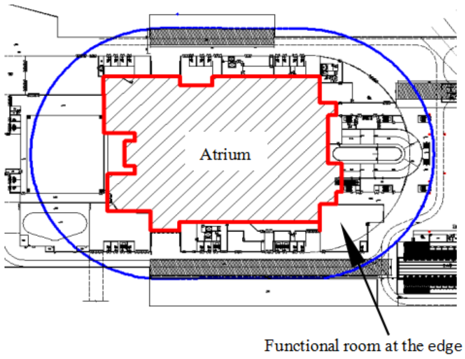

Figure 1: Floor plan.

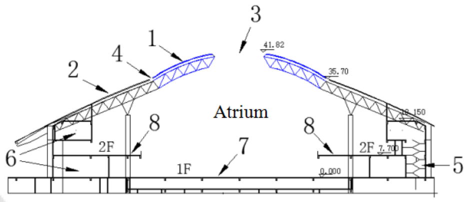

Figure 2: Building cross-sectional view.

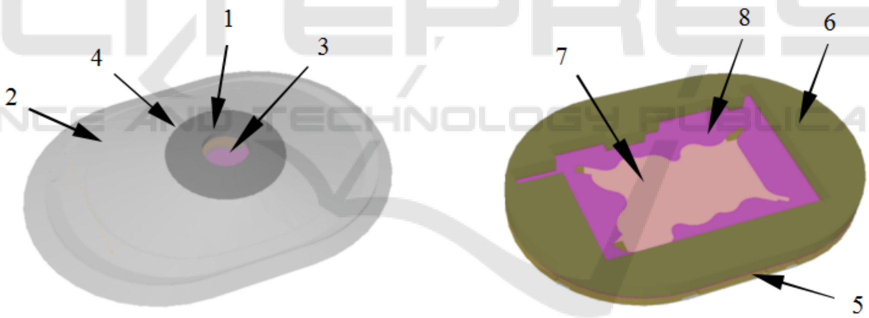

Figure 3: Building simplification model.

1- Round glass roof, 2- Slope roof of the membrane material, 3- Circular exhaust vent at the top (in the middle of the glass roof), 4- Annular exhaust vent in the side (at the junction of 1 and 2), 5- Inlet vent (doorway and windows of first and second floor), 6- Functional room on the edge of the atrium, 7- First floor staff activities area, 8- The second floor staff activity area.

2.2 Mathematical Model

The PHOENICS 2016 software is used to simulate the calculation. The k-ε two-equation turbulence model is chosed to solve the indoor flow field.

Ideal fluid model and Boussinesq assumption are used, too. The SIMPLE algorithm and the second-order upwind scheme are adapted to calculate the flow field. Besides, instead of using the solar radiation model, this paper converts solar radiation heat into a specific heat source located below the glass roof and on the atrium floor.

2.3 Boundary Conditions

Indoor heat source mainly considers the body heat, equipment heat, lighting and solar radiation. And all types of heat sources are set according to the standard values in the specification. The main design parameters are: total personnel heat output 480.67kW; light heat 223.68kW; equipment heat 559.20kW; solar radiation heat 1242kW.

The wet source only comes from the human body, the amount is 240g/h·p (moderate labor), and the cluster factor is 0.85, so the total amount of wet is 324.50g/s.

According to the statistics of Zhuhai Meteorological Bureau for several years, the average outdoor air temperature is about 22 ℃ and the relative humidity is about 85% in the hot summer and warm winter zone in transition season (spring). Due to the uncertainty of outdoor wind speed and direction, this study only considers the effect of natural ventilation under thermal pressure.

2.4 Mesh

The method of using an evenly distributed grid which may far beyond the load that the computer can carry is unreasonable. Therefore, this paper uses the method of grid local encryption to carry out special treatment to the location of the inlet and outlet and the key area of study. Because the models of various conditions are different, the number of grids is slightly different with the number between 712800~977400.

The convergence criterion is that the ratio of the residual value of the last iteration to the previous residual value is less than $10e^{-3}$.

2.5 Simulation conditions

The experiment simulates the combination of three kinds of exhaust port position and four different exhaust port area in the atrium under natural ventilation, and the specific conditions are shown in Table 1 :

Table 1: List of conditions.

<table>
<tr><th>Condition</th><th>Top vent area (m²)</th><th>Side vent area (m²)</th><th>Description</th></tr>
<tr><td rowspan="4">Full top opening</td><td>100</td><td>0</td><td rowspan="12">The top air outlet is located in the center of the circular glass roof, whose shape is a circle.
The side vent is located at the junction of the glass roof and the roof of the membrane material, with a position of 35.7m and a ring shape.
Inlet vent is the door and window of the first and second floor, with a total area of about 500m².</td></tr>
<tr><td>250</td><td>0</td></tr>
<tr><td>500</td><td>0</td></tr>
<tr><td>750</td><td>0</td></tr>
<tr><td rowspan="4">Full side opening</td><td>0</td><td>100</td></tr>
<tr><td>0</td><td>250</td></tr>
<tr><td>0</td><td>500</td></tr>
<tr><td>0</td><td>750</td></tr>
<tr><td rowspan="4">The opening areas of the top and side are in equal measure</td><td>50</td><td>50</td></tr>
<tr><td>125</td><td>125</td></tr>
<tr><td>250</td><td>250</td></tr>
<tr><td>375</td><td>375</td></tr>
</table>

3 SIMULATION RESULTS AND ANALYSIS

3.1 Indoor Temperature and PMV Analysis

Through simulating of software and visualization of the results, the temperature and PMV of each solution are obtained as shown in Fig. 4 to Fig. 8. The personnel activity area is located in the position that 1.5m vertically from the floor, which is the average height of the person's head.

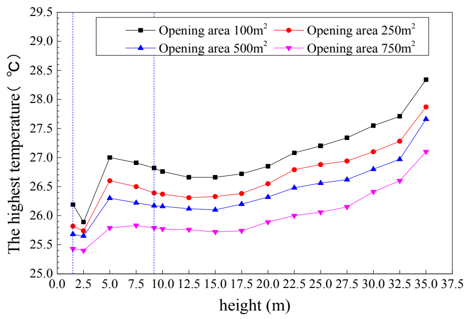

Figure 4: The highest temperature of full top opening condition.

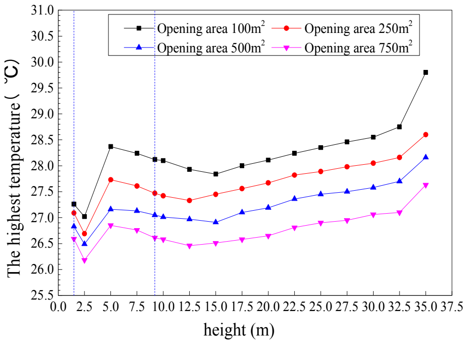

Figure 5: The highest temperature of full side opening condition.

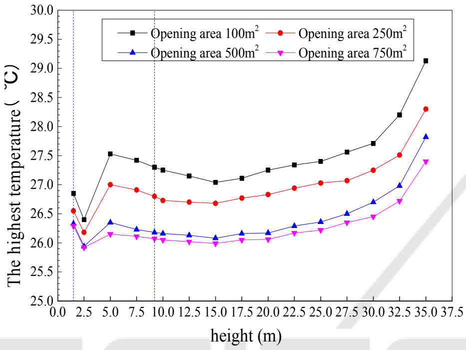

Figure 6: The highest temperature of the opening areas of the top and side are in equal measure condition.

(Note: The two dashed lines (height of 1.5m and 9.2m) perpendicular to the X axis are the height of the active area of the first and second floor, respectively.)

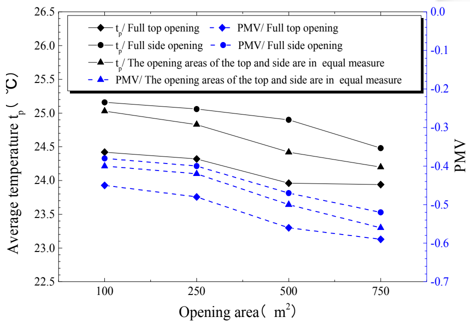

Figure 7: The average temperature and PMV of the first floor personnel activity area.

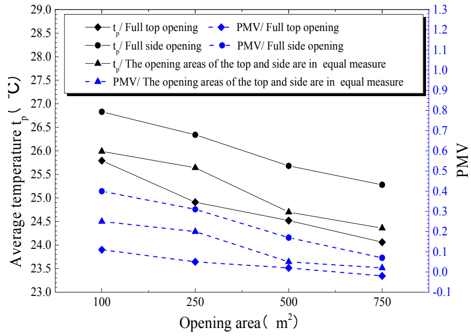

Figure 8: The average temperature and PMV of the second floor personnel activity area.

Fig. 4, 5 and 6 show the vertical maximum temperature of the conditions. The atrium has obvious vertical temperature stratification along the height direction. The general trend is that the higher the vertical height, the higher the temperature. The average temperature difference between the bottom and the roof is about 2℃, which accords with the existing research (T Yu, L Yang, 2012) on measured thermal environment in atrium. This is because of the chimney effect. Moreover, due to the buoyant force, the indoor air with a higher temperature moves to the top of the space and forms a vortex near the roof, causing the heat to stagnate. In addition, the atrium has a clear greenhouse effect, and the sunlight through the glass of radiant heat gathered below the roof, exacerbating the temperature rise.

However, the temperature decreases first and then increases and decreases finally in the height of 1.5m ~ 12.5m range, in which the extreme values appear in the active area between the first and second floor. This is due to the fact that staff activities area (1.5 m in height) in first floor is larger in area and generates more heat, resulting in a higher temperature. The hot air flow on the ground floor moves vertically upwards by the buoyant force, however, the temperature drops to a certain extent (the average temperature drop is about 0.3℃) at 1.5m due to the dilution effect of outdoor entering cold wind. The thermal air flow continues to move upwards and is blocked by cold air at the inlet vent (7.7m ~ 9.7m) on the second floor. A part of the hot air flow stays between the first floor and the second floor, resulting in a higher temperature in this interval, where the maximum is at 5m. The second floor activity area (9.2m height) is only a stretch of walkway along the wall with less heat and it is the same height as the air inlet. Thus, the temperature is lower. The cooling effect of the cold air flow on the indoor air lasts until the height of 12.5m is reached.

And because the heat radiation caused by sunlight getting through the glass roof is getting stronger, the temperature begins increasing slowly.

At the height of 32.5m~35m, the temperature shows a significant increase not only because the 35m is close to the glass roof, but the heat radiation of the glass becomes stronger after glass absorbing heat. Besides, being limited by natural ventilation, the heat flow rising from the bottom forms a certain degree of eddy currents at the roof, making the heat accumulation more seriously. As a result, there is a sudden temperature rise here.

In the same condition, that is, when the opening position is fixed, different air outlet size results in different indoor thermal environment effects. However, in the scenario simulations at three different locations, the maximum temperature of the corresponding position decreases with the increase of the opening area, and the average temperature difference of the adjacent outlet area condition is about 0.5℃.

When the area of the opening is fixed, it is found from the comparison of the corresponding height of the three conditions that the temperature of the full-top opening solution is the lowest, followed by the half-top & half-opening solution, and the worst effect appears in the full-side opening solution, which is also consistent with the characteristics of the movement of heat flow. Heat flow raising is gathered at the roof, the higher the location is, the closer the roof of the place is, the more benefits we get to boost the diffusion of heat flow, and the better the cooling effect is. At the same time, increasing the outlet height can not only effectively increase the position of the neutralizing surface (LW Zeng, 2015) and increase the pressure on the inlet side, but also promote the inflow of cold air at the bottom of the building, and also promote the air flow to a certain extent.

Fig. 7 and 8 show the average temperature and PMV comparison of the first and second floors of the conditions respectively. The figure shows that PMV has a strong positive correlation with the temperature. The area with the lower temperature, PMV is smaller, PMV in the area with the higher temperature is also larger, and the amplitude of change is also very consistent.

3.2 Indoor Ventilation Effect Analysis

Indoor ventilation effect affects the body's thermal comfort to a large extent, which can be judged by ventilation efficiency and ventilation frequency.

Ventilation efficiency indicates the capability of blowing air to eliminate indoor residual heat pollution or chemical pollution. And in terms of waste heat, it can also be called temperature efficiency (JH Meng, 2005). It is a concentrated reflection of the comprehensive effect of indoor thermal environment (XJ Meng, G Du, 2013), and can be calculated as follows:

$$E = \frac{t_p - t_o}{t_w - t_o} \tag{1}$$

In the formula: t_p - Exhaust temperature, ℃; t_o - Inlet temperature, ℃; t_w - Personnel activity area temperature, ℃.

Ventilation frequency is not only an important parameter that measures the pros and cons of indoor air dilution or the degree of mixing achieved by dilution, but also an estimate of the indoor ventilation rate, which can be calculated as shown (R Zhang, PF Fang, 2017):

$$N = \frac{3600 * Av}{V} \tag{2}$$

In the formula: N - Ventilation frequency, times / h; A - The total area of the inlet vent, m^2; v - The average inlet speed, m/s; V - The volume of the building, m^3.

Table 2, Fig. 9 and 10 show the calculation results of ventilation efficiency and ventilation frequency of each condition.

Table 2: Natural ventilation efficiency and ventilation frequency of each condition.

Condition		Exhaust temperature t_p (℃)	Into the air temperature t_o (℃)	Personnel activity area temperature t_w (℃)	Ventilation efficiency (η)	Average inlet vent velocity (m/s)	Average air age (s/time)	Ventilation frequency (times/h)
Full top opening	100m^2	28.02	22.00	25.16	1.91	1.03	733.00	4.91
	250m^2	27.87	22.00	24.57	2.28	1.08	700.69	5.14

	500m^2	27.66	22.00	24.35	2.41	1.15	657.94	5.47
	750m^2	26.99	22.00	24.00	2.50	1.24	611.33	5.89
Full side opening	100m^2	28.31	22.00	26.00	1.58	0.76	990.15	3.64
	250m^2	28.15	22.00	25.70	1.66	0.97	782.37	4.60
	500m^2	28.08	22.00	25.46	1.76	1.05	719.04	5.01
	750m^2	27.31	22.00	24.88	1.84	1.14	663.73	5.32
The opening areas of the top and side are in equal measure	100m^2	27.96	22.00	25.49	1.71	0.96	786.45	4.58
	250m^2	27.93	22.00	25.23	1.84	1.06	715.63	5.03
	500m^2	27.13	22.00	24.56	2.00	1.10	684.80	5.26
	750m^2	26.63	22.00	24.28	2.03	1.15	659.38	5.46

(Note: The exhaust temperature t_p is the average temperature of all vents, the temperature of the active area t_w is the average temperature of the active area of the first and second floor.)

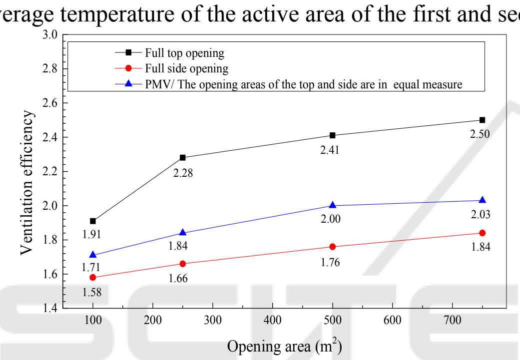

Figure 9: Natural ventilation efficiency of each condition.

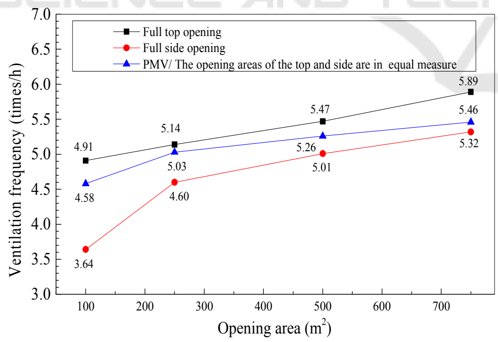

Figure 10: Natural ventilation frequency of each condition.

As can be seen from Table 2, Fig. 9 and 10, the ventilation efficiency and ventilation frequency of the project are the lowest when the opening area is 100m^2. But they gradually increases as the opening area increases, while the overall increase gradually tends to be flat. In the design condition with three different opening positions, the ventilation efficiency and the ventilation frequency of the top opening are the highest, followed by the top and the side portions respectively being 1/2 each, and these sectors of the whole side opening are the worst. The larger the area of the air vents is, the better the ventilation efficiency in the room is, the faster the heat and pollutants are diluted, but it also means that the indoor temperature field is relatively non-uniform (XJ Meng, G Du, 2013), which may affect the body's thermal comfort to some extent.

As the area increases, the ventilation efficiency and ventilation frequency increase slower and slower, indicating that the change of the area of the smaller exhaust vent has a great influence on them. It can also be inferred that the area increases to a certain extent, the ventilation efficiency and ventilation frequency will gradually reach the maximum and almost be steady. The difference in the ventilation efficiency of the exhaust vents at different locations is that the thermal pressure keeps the air flow rising toward the top of the atrium and the closer the distance to the top is, the better the effect of heat diffusion is, and the larger the area or the area occupation ratio of the top vents is, the better the effect of heat diffusion is.

3.3 Energy Conservation Evaluation of Wind Energy Utilization

As Zhuhai is located in hot summer and warm winter area, air conditioning systems are still needed in some stages of the transition season to regulate the indoor environment. Therefore, in order to measure the energy-saving effect of wind energy utilization of the atrium building, this paper estimates the energy consumption of the building during the transition season for the following two kinds of ventilation and air-conditioning operation strategies:

- Strategy one: using air-conditioning system in the whole process.
- Strategy two: using pure natural ventilation first, then air-conditioning system while outdoor temperature is above 24 ℃.

According to the existing research (YB Lu, 2014) about the energy-saving rate of natural ventilation in the hot summer and warm winter area, strategy two is more energy-efficient than strategy one in a 3.5m high large space building with a non-atrium structure in the transition season in Guangzhou, with 62.9% energy-saving rate. In contrast, the building studied in this paper not only has the atrium structure with a glass roof, but also has a height of 41.82m which is much higher than normal buildings. Therefore, the building will have more significant chimney effect and stronger heat ventilation, making the energy-saving rate higher.

It can be inferred that natural ventilation has a significant energy-saving effect on tall atrium buildings, and the energy-saving rate can reach more than 62.9%, meeting the preferred requirements of the green building that the energy-saving rate must be 60%.

4 CONCLUSION

By reasonably setting various calculation parameters of PHOENICS, 12 kinds of natural ventilation conditions with different outlet location and area are simulated, and we can draw following conclusions：

- Due to the heat pressure, air with high temperature at the bottom of the room moves closer to the middle of the atrium and upwards, causing the high temperature gas to form a vortex below the roof, which results in the accumulation of heat. Meanwhile, as the glass roof has a significant greenhouse effect, heat radiation that through the glass gathered under the roof, exacerbating temperature rise. So there is a higher temperature near the roof than temperature at the bottom of the activity area. At the same time, it is found that PMV has a strong positive correlation with temperature. PMV is smaller in the lower temperature region and larger in the higher temperature region.
- The location and area of the top vents greatly affect the atrium in temperature, PMV, ventilation efficiency and air frequency. The effect of natural ventilation caused by the thermal pressure as well as upward movement of neutralization surface can be more obvious and the utilization of wind energy can be higher with higher location and larger area of the vents. Besides, the indoor temperature, PMV, ventilation efficiency and ventilation frequency can be greatly improved. Although the ventilation efficiency, ventilation frequency and exhaust outlet area have a significant positive correlation, with the increase of area, the increase in ventilation efficiency and air frequency tends to moderate, indicating changes in the smaller exhaust port have a greater impact on them. And it can be deduced that when the area of the air outlet increases to a certain extent, the ventilation efficiency and air changes will gradually increase to the maximum and remain basically stable. This is because when the exhaust vents are larger than the inlets, the area of the inlets becomes a major factor affecting increase of air volume (HQ Tang, 2008), making the ventilation efficiency and air frequency increasing more and more slowly.
- Natural ventilation has a significant energy-saving effect on tall atrium buildings, and the combination of natural ventilation and air conditioning energy-saving rate may reach more than 62.9%, compared to the entire use of air conditioners.

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