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Building Energy Efficiency Simulation of Retractable Roof of Gymnasiums

Shuai Zhang, Li Yang*, Kuan Zhou

College of Architecture & Urban Planing, Tongji University, Key Laboratory of Ecology and Energy Saving Study of Dense Habitat (Tongji University) by Ministry of Education, 1239 Si Ping Road, Shanghai, 200092 China
yangli.arch@tongji.edu.cn

The purpose of this study is to explore the adaptability of the retractable roof of stadium buildings to the external climate, and then to explore the energy-saving effects of the retractable roof on stadium buildings. This study takes the Jiading Gymnasiums of Tongji University in Shanghai as an example, and it uses digital simulation technology to apply AIRPAK CFD multiphysics simulation software to perform digital simulation analysis of the two operating conditions of Jiading Gymnasium. Using the somatosensory temperature and the Predicted Mean Vote (PMV) as control indicators, the indoor environment of the two working conditions was analyzed. The experimental results show that retractable roof can effectively improve the indoor environment. It is concluded that the retractable roof of the stadium can effectively adjust the indoor environment of the building by opening and closing, improve the comfort of the indoor thermal environment, and reduce the energy consumption of the stadium.

1. Introduction

The structure of the stadium is different from other kinds of architecture. Because of its big size and lager inner space, as well as the specific requirements set to provide a suitable light and thermal inner environment for athletes and audience while there is a match, the amount of energy consumption caused by the air conditioner and illumination is huge (Yang et al., 2019). How to take full advantage of passive energy-saving technology under the premise of comfort becomes the key point of the energy-saving design of a stadium (Yang, 2017). In the study of the retractable roof, Xu and Wu (2013) studied the lightning protection design of the retractable roof. As early as 2008, Yan (2008) conducted an in-depth analysis of the retractable roof technology used in Nantong Stadium. Bonser et al. (2020) analyzed the influence of the opening and closing of the hot climate on the wind and thermal environment of the football field. Kim et al. (2019) conducted an in-depth study of characteristics of wind pressures on retractable roof. It can be seen that the previous researches by the scholars on the retractable roof mainly focused on the structural design and durability of the retractable roof, and also studied the influence of the retractable roof on the wind environment and the thermal environment. There are few studies on the indoor environment. The innovation of this study is the introduction of PMV evaluation method and somatosensory temperature, and the use of digital simulation to study the retractable roof and predict its energy-saving effect.

2. Green and energy saving design

2.1 General Situation of the Building

Tongji Sports Centre in Jiading locates in the north of Jiading campus, Tongji University. To the east of the centre is the dormitory area and the Xiaowu pond lies to the west. The project covers an area of 9,169 m^2 and has a gross floor area of 13,410 m^2. And the height of the building is 19.7 m. The main body is covered by glass curtain wall and aluminium pannels. The aluminum canopy curtain wall, the glass curtain wall with exposed vertical frames and concealed horizontal frames, as well as the gradient aluminium and glass curtain wall, are

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the main kinds of the curtain wall that were used in Tongji Sports Center in Jiading. By using these and taking good advantage of natural light, a lot of artificial illumination can be avoided and energy is saved.

he stadium adopts the integrated design of the beam string structure and the light pipes. It has a roof with 45-meter-long-span steel beam string structure, which is quite light. Traditional lighting equipments are retained at the top of the stadium. In order to make the indoor space well-aligned, the light pipes are embedded in the girders of the string beam structure. By doing that, some general problems of light pipes can be avoided. It also reduces the energy consumption of illumination by introducing the natural light and the indoor space quality is improved as well (Yang, 2016).

2.2 The Calculation of Apparent Temperature

The empirical formula for the apparent temperature is as follows:

$$Tg = Ta + Tr + Tu - Tv \tag{1}$$

In this formula, Tg refers to the apparent temperature; Ta refers to the real temperature; Tr is the correction of the apparent temperature under the influence of radiation; Tu is the correction of the apparent temperature under the influence of humidity; Tv is the correction of the apparent temperature under the influence of wind speed. The apparent temperature involves five kinds of meteorological factors which are temperature, the colour of clothes, cloud cover (or solar radiation), humidity, and wind speed. When talking about the correction of the apparent temperature under the influence of radiation, there is an empirical formula as follows:

$$Tr = 0.42Ca(1-0.9Mc)Ia \tag{2}$$

In this formula, Ca refers to the ability of the outerwear to absorb radiation. In summer, most people wear light colours, and they tend to wear dark colours in winter. Taking this point into consideration, Ca is set to 0.4 in the summer half-year (from May to October). And in the winter half-year (from November to April), Ca is set to 0.75. Mc refers to the cloud cover coefficient. When there is more cloud, the temperature rises less through radiation. Generally, Mc is set to 0.0 in a sunny day, and 0.3 when it is partly cloudy. In a cloudy day it is set to 0.7, and 1.0 when it is overcast. Ia represents the radiation warming coefficient. At the same temperature, the stronger the solar radiation is, the hotter the human body feels.

The correction of the apparent temperature under the influence of humidity (Tu) is shown in Table 1 (Luo and Chen, 2002). When the temperature is moderate, the humidity has little effect on the comfort of the human body. When the temperature is high or low, the humidity changes have an effect on the body feeling. The correction of the apparent temperature under the influence of wind speed (Tv). Wind speed plays an important role in the regulation of human body temperature. It determines the convective heat dissipation of the human body and affects the evaporation ability of the air so as to indirectly affect the heat dissipation efficiency of sweating. Convective heat dissipation is related to temperature, and the effect of wind speed on evaporation is related to relative humidity. The reference index is shown in Table 2.

Table 1: The relation between Tu and average relative humidity

RH (%)	100	90	80	70	60	50	40	30	20
Tu (^{0}C)	3	2	1	0	-1	-2	-3	-4	-5

Table 2: The relation between Tv and average Wind Speed

Wind Speed	0.3-1.5	1.6-3.3	3.4-5.4	5.5-7.9	8.0-10.7	10.8-13.8	13.9-17.1	17.2-20.7
Tv(^{0}C) in Shanghai	2.4	3.5	3.9	4.4	4.6	4.8	5.1	5.2

3. Comfort analysis

Humidity and temperature directly affect the sensible heat exchange of convection and radiation of human body (Yang et al., 2020). The human body feels rather sensitive to temperature and temperature is the most important factor affecting thermal comfort. The human body doing sports has the following characteristics: the metabolic rate is high, the thermal resistance of the clothing is small, the volume of perspiration is large, and the radiation environment is complex, so the thermal comfort of the human body when doing sports is very different from that in the quiet state (Wang and Hu, 2014). The speed of air flow has both positive and negative effects. First, in a hot environment, air flow can provide fresh air to the human body and cool the body, making the human body reach thermal comfort. It also accelerates the convection and evaporation of heat dissipation of the human body to some extent. The excessive air flow may also cause a risk of blowing. At the same time, there is a certain correspondence between the apparent temperature and the feeling of the human body (Ji et al., 2017), as shown in Table 3.ºC

Table 3: Apparent temperature and corresponding body feelings

Tg (ºC)	Body Feeling	Physiological Stress Level
＜4	Very Cold	Extreme Cold Stress
4-8	Cold	Intense Cold Stress
8-13	Cool	Moderate Cold Stress
13-18	Slightly Cool	Mild Cold Stress
18-23	Moderate	No Heat Stress Reaction
23-29	Slightly Warm	Mild Heat Stress
29-35	Warm	Moderate Heat Stress
35-41	Hot	Intense Heat Stress
＞41	Very Hot	Extreme Heat Stress

4. Energy-saving features of the natatorium when the roof is opened or closed

4.1 Initial conditions in summer

Since the natatorium and the stadium’s roof are covered with thermal insulation materials, there is no heat exchange between the indoor space and the surrounding environment, and the surface condition is set to adiabatic. Because this study is a typical simulation at no audience in the summer, the indoor electrical load mainly comes from illumination. On the top of stadium there’s a circular cylinder with a diameter of 580 mm and 76 light pipes are installed combining with vertical poles. The light load is calculated to be 40 W each light pipe. Each pipe is seen as a heat source. Since the indoor heat exchange of heat sources involves two processes: radiation heat transfer from the light source to the surrounding air and convection exchange, light loads are divided into the convection part and the radiation part according to the radiation load calculation method and they will be set respectively for the model. Outdoor thermal environment parameters are set according to the Chinese meteorological data set of thermal environments of building. The outdoor temperature is set to 31.3 ^{0}C, and the wind speed is set to 3.4 m/s. The wind direction is set to south, and the intensity of solar radiation is set to 18.64 MJ/m^2. When it comes to indoor design parameters, the summer indoor temperature is set to 28 ^{0}C, and relative humidity is set to 60 %. Because the surface is under adiabatic condition, the indoor temperature is set to 28 ºC.

4.2 Model establishment

When building the model of the sports center, only the natatorium, stadium and outdoor stands parts are chosen to be established. The natatorium is 70 m long, 35 m wide and 15.8 m high. And the stadium is 70 m long, 53.5 m wide and 19.6 m high. When the roof is closed, the air supply of the natatorium is borne by the ventilation windows on the north and south facades. When the roof is opened, the air supply comes from the opened roof as well as the ventilation windows on the north and south facades, which are placed according to the actual situation. The type of swimming pool’s model is set to fluid and the temperature is set to 25 ºC according to the national standards. The specific heat capacity is set to 4.2 x 10^3 J/(kg ºC), to adequately simulate the indoor environment. A total of 72 light pipes are installed on the top of the stadium, which is 17 m high. The power of each light pipe is 40 W (Cheng and Luo, 2015). On the north and south walls of the stadium, there are each 5 air outlets and the centre height of outlet is set according to the actual situation. On the east side, there are 6 outlet s, and the centre is 15 m. The size of each outlet in the model is simplified to be 1.4 m wide and 1.8 m long. According to the external climate conditions, the outdoor wind speed is set to 3.4 m/s, and the wind direction is southward. The outlet s close to the south side is set as above, while the northward outlet s are only set the type to open and wind direction or speed are left alone, to form a natural ventilation path (Yang et al., 2019). The part of the roof that can be opened or closed is a collection of aluminum pannels and glass curtain walls. when the roof is closed, the translucent glass material will be given to the part of the curtain wall, so that the solar radiation can enter the indoor. At the same time, to save the simulation time, when the roof is open, the glass part does not have the protective effect and there is no need to assign the material. Since this research mainly focuses on the influence of the retractable roof on the indoor environment, and then explores its energy-saving effect, the working conditions are set to two types, one is the retractable roof closing equipment, and the other is the retractable roof 100% open state. Do not consider other open areas.

5. Analysis of the results

5.1 Velocity analysis

As can be seen from the velocity cloud diagram (Figure 1a and Figure 2a), the indoor velocity distribution is relatively stable. The speed is small, and no large vortex appears.

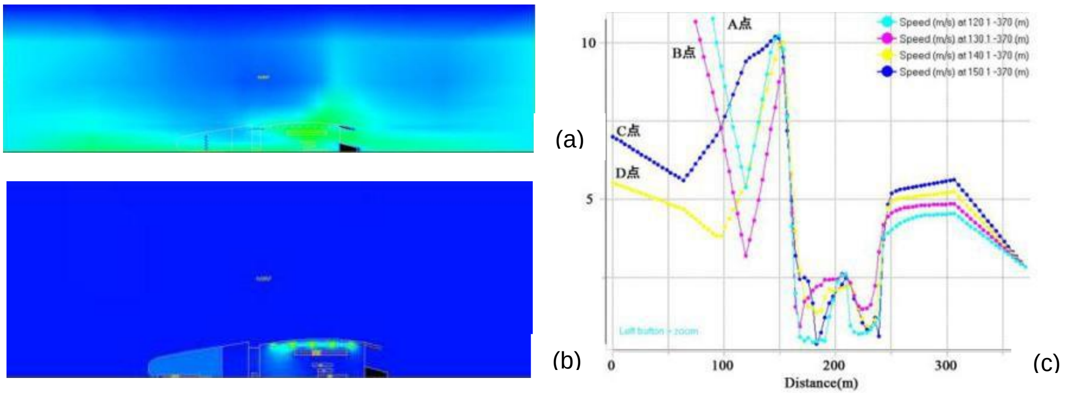

Figure 1: (a) Z = 170 Velocity Cloud Diagram (roof closed), (b) Z = 170 Temperature Cloud Diagram (roof closed), (c) X = 120 - 150 Y = 1 Z = 170 Flow Velocity Diagram (roof closed)

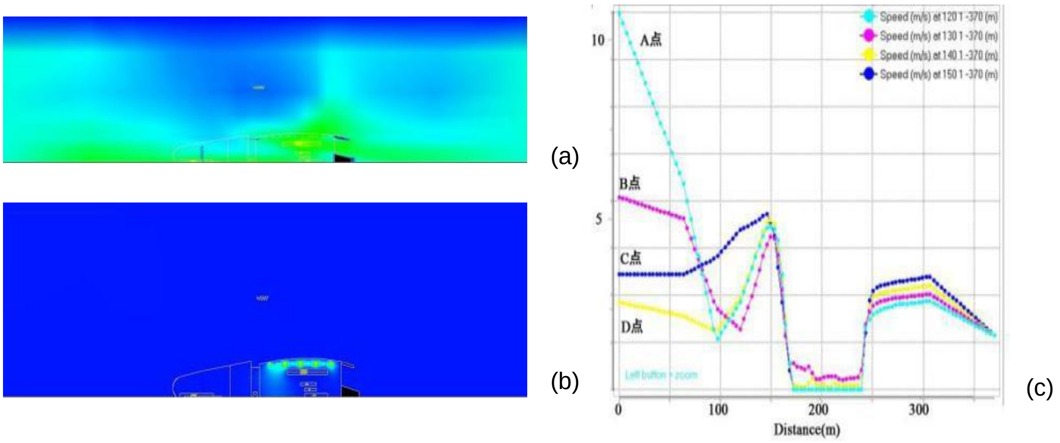

Figure 2: (a) Z = 170 Velocity Cloud Diagram (roof opened), (b) Z = 170 Temperature Cloud Diagram (roof opened), (c) X = 120 - 150 Y = 1 Z = 170 Flow Velocity Diagram (roof opened)

When the roof is closed, the indoor air exchange is only carried out by several windows of the stadium next to the natatorium, so the wind speed is low. The indoor wind speed in the natatorium is below 1.5 m/s. When the roof is opened, the natatorium becomes a semi-outdoor open space, and the indoor wind speed increases relatively, and the wind speed is 1.5 - 2.5 m/s. Compared with the speed when the roof is closed, the indoor wind speed increased by nearly 6 times. Because of the requirements of different types of sports in the stadium, the natatorium is separated from the stadium to ensure a small wind speed. The average wind speed is about 0.2 m/s. In relevant regulations the speed should be less than 0.2 m/s. More can be seen from the flow velocity diagram, especially from point A (X = 120 Y = 1 Z = 170), point B (X = 130 Y = 1 Z = 170), point C (X = 140 Y = 1 Z = 170) and point D (X = 150 Y = 1 Z = 170) (Figure 1c and Figure 2c). When the roof is closed, the streamline in the swimming pool is relatively gentle and stable. After the roof is opened, the indoor streamline has obvious fluctuation. The wind speed value corresponding to the four curves of A, B, C and D increases compared with the original curve.

5.2 Temperature analysis

From the temperature diagram of the section (Figure 1b and Figure 2b), it can be seen that the temperature distribution gradient in the swimming pool is relatively small, in the range of 27 - 29 ºC. When the roof is closed, the indoor temperature of the natatorium is around 29 ºC. The temperature near the roof is high, and the temperature of the swimming pool is relatively low, mainly because of the small density of hot air which is almost in the upper part of the space. When the roof is opened, the indoor wind speed increases due to the effect of wind pressure, and the corresponding convective heat transfer coefficient increases as well. The overall temperature inside the room decreases to about 27 ºC. When the roof is opened, the indoor temperature decreases by about 1 - 2 °C. The degree of decline is about 6.8 % of the original.

5.3 Analysis of thermal comfort evaluation

The predicted mean vote value (PMV) was proposed by Fanger in the 1970s, and its value ranges from -3 to +3, representing seven thermal sensations (Fanger, 1967). It has certain limitations in the evaluation when the subjects are in moderate to an intense activity or the thermal resistance of clothes is high and may lead to a large error. It can be seen that PMV index has some limitations in measuring thermal comfort. In this article, the thermal comfort of the human body in intense activity is the object of Research. Compared with PMV, apparent temperature is more intuitive and has a closer connection with the human body itself. Especially when the human body is under special conditions, such as in intense activity, the measurement of PMV may lead to a certain error while the apparent temperature can directly measure the human body's own feeling and has fewer limitations. In this paper, apparent temperature is selected as the main evaluation standard and PMV is selected as an auxiliary measurement standard. Both the wind speed and temperature affect the thermal comfort to some extent. According to Moderate-thermal-environments—Determination of the PMV and PPD indices and specification of the conditions for thermal-comfort (GB 18049-2000-T), when the PPD index is less than 10 %, it represents that the thermal environment is acceptable (Fanger, 1985). The value of PMV is between -0.5 and 0.5 according to the corresponding conditions between PPD and PMV (seen from Table 4).

Table 4: The relation between PMV value and thermal sensation

Thermal Sensation	Hot	Warm	Slightly Warm	Moderate	Slightly Cool	Cool	Cold
PMV	+3	+2	+1	0	-1	-2	-3

According to the correspondence between PMV and thermal sensation (seen from Table 4), the indoor comfort is between slightly warm and cool, including the optimal comfort condition when PMV = 0, and belongs to the interval of -0.5 to 0.5. When the roof is closed, the indoor PMV value is between 0.0625 and 0.25. The indoor thermal comfort at this time is slightly warm, and does not include the optimal thermal comfort when PMV is 0, but is still in the range of -0.5 to 0.5. When the roof is closed, the indoor thermal comfort can still meet the requirements of the human body. But in the summer, when the roof is opened, the wind speed and temperature conditions in the natatorium are better than when the roof is closed. The indoor thermal comfort level is higher and can reach the optimal thermal comfort when the roof is closed. Also, the predicted percentage dissatisfied (PPD) is 1 % lower than when the roof is opened. However, since the evaluation index of PMV is mainly aimed at the subjects who sit still, it is necessary to supplement the apparent temperature for the human body in intense activity in this Research. When the roof of natatorium is closed, the apparent temperature can be calculated by putting the corresponding Ta, Tu, Tr, Tv into formula (1) and the result is 25.77 ºC. When the roof is opened, through corresponding calculation Tg is 23.67 ºC. After the roof is opened, the apparent temperature has reduced by 8.15 %. It can be seen from Table 3 that when the roof is closed, the human body feels warm at this time and a slight heat stress reaction appears. When the roof is opened, through corresponding calculation the apparent temperature is 23.67 ºC.

6. Conclusions

According to the Chinese Building Design Code JGJ 31-2003 "Sports Building Design Code", the indoor standard summer temperature of the swimming pool is 28 ºC, and the Jiading Sports Center has a somatosensory temperature of 23.67 °C after opening the retractable roof, which is 4.33 ºC lower than the standard requirements. According to related research, the indoor temperature has dropped by 1 ºC, and the energy consumption of the air conditioner has dropped by 7.96 %. Calculated according to the summer working conditions, because not all air conditioners are always used to regulate the indoor environment, by using AIRPAK software for simulation calculations, it is estimated that the use of retractable roof can reduce air conditioning energy consumption in buildings by 5.2 %. The innovation of this study is that the CFD technology is used to simulate the adjustment effect of the retractable roof on the indoor environment of the swimming pool. The use of data proves that the retractable roof can expressly adjust the indoor environment and reduce building energy consumption. It also proves the positive effect of the new building technology of opening and closing the roof on improving the indoor environment of the building. CFD simulation research methods have been widely used in wind environment and heat transfer of building components. However, the CFD method is rarely applied to the impact of the opening and closing roof on the indoor environment. Compared with the traditional on-site testing method, the CFD method is more intuitive, faster, and reduces the use of manpower and material resources. Compared with the actual testing method, the simulated data is closer to the actual situation due to the unstable outdoor environment. The outdoor environment used in this study is the outdoor environment specified by the Chinese national standard, which is an average value, so it has certain limitations for extreme climate environments. Although all the methods used in this article have obtained a large amount of data, they need to be further confirmed by the field test data.

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