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Numerical Analysis of Improvement Effects on Summer Outdoor Thermal Environment Around Enclosed Teaching Buildings in the Hot-Humid and Less-Windy Climate

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Abstract. Outdoor thermal environment around teaching buildings affects students' comfort and building energy consumption, especially in summer. This paper focuses on a teaching building with enclosed arrangement in a hot-humid and less-windy climate and analyzes the thermal environment in outdoor spaces around the building. The measurement results showed that average air temperatures and MRT (mean radiant temperature) in six outdoor spaces are higher than the ambient temperature by around 1 °C and 6 °C, respectively. Thermal improvement strategies for reducing surface temperatures in the analyzed spaces were proposed based on measurement results. A thermal simulation tool (ThermoRender) was used to quantify the improvement effects of the proposed strategies on the thermal environment. Simulation results revealed that the average values of MRT were reduced by 1.0 °C to 5.1 °C. It is noted that the reduction of received solar heat through sunshade devices and tree shading is an effective way to improve outdoor thermal environment, which can be considered as design guidance for creating a comfortable outdoor thermal environment around enclosed teaching buildings in the hot-humid and less-windy climate.

Keywords: Outdoor thermal environment · Enclosed building · Sun shading · Hot-humid and less-windy climate · Numerical analysis

1 Introduction

Teaching buildings are the main places for teachers and students to study, work and communicate in campuses. A comfortable thermal environment is conducive to improve the efficiency of work and study [1–3]. At present, the thermal environment in teaching buildings has been concerned by many researchers. However, most of the related researches focused on the thermal environment in indoor spaces [4–9]. Teaching buildings include not only the indoor space for work and study, but also the outdoor space for communication, rest and exercise. Appropriate rest and activities can relieve work stress and ensure the health of teachers and students. More importantly, the thermal

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W. Guo et al. (Eds.): GBCESC 2023, LNCE 328, pp. 511–519, 2024.
https://doi.org/10.1007/978-981-99-9947-7_53

environment in outdoor spaces is an important factor for improving the willingness of students to conduct outdoor activities and reducing the building energy consumption, especially on summer days. Therefore, it is necessary to improve the outdoor thermal environment around teaching buildings in summer by taking measures. At present, thermal improvement strategies are universally adopted to different buildings [10]. It is an effective way to determine the improvement strategies according to the characteristic of analyzed spaces. Additionally, the hot-humid and less-windy climate is characterized by abundant solar radiation, low wind speed and prolonged discomfort period in summer. The improvement of outdoor thermal environment around buildings in the hot-humid and less-windy region is significantly urgent.

In terms of the outdoor space formed by enclosed buildings, it has more potential to enrich outdoor environments by adding pool, greening, exercise field, etc. However, this enclosed layout has some negative impacts on the thermal environment in outdoor spaces, such as the excessive solar heat and poor natural ventilation. It is necessary to improve the thermal environment in outdoor spaces around enclosed teaching buildings through appropriate improvement strategies. At present, there is still a lack of quantitative analysis on the outdoor thermal environment around enclosed teaching buildings in the hot-humid and less-windy climate.

Therefore, this study aims to analyze the characteristics of outdoor thermal environment around enclosed teaching buildings and quantify the improvement effects of the proposed strategies on the thermal environment. A teaching building in Nanning was selected as the research object. Thermal improvement strategies were proposed according to analysis results from field measurement, and their improvement effects were quantified using a thermal simulation tool (ThermoRender).

2 Methodology

2.1 Description of Study Building

The study building is the No.4 teaching building at a university which is located in Nanning (N22′ 13′ ~ 23′ 32′, L107′ 45′ ~ 08′ 51′), China. An aerial view of the building and the layout of the first floor are shown in Fig. 1(a). It is a typical enclosed building composed of two parts i.e. the north building with 7 floors and the south building with 2 floors. The two parts are connected by corridors. The study building covers an area of 4400 m^2 with a construction area of around 33600 m^2, and is mainly included classrooms, activity rooms, etc. The ground around the building is concrete-paved.

Two courtyards are formed by the north and south buildings, covering an area of about 1200 m^2 and 500 m^2, respectively. The large courtyard has two badminton courts with plastic-paved ground and a L-shaped pool, and most of its ground is paved by hard tiles. There is few vegetation (lawn and trees) in the large courtyard. On the east side of the small courtyard, there is a pool which is surrounded by lawn and several trees. Since the teaching building is frequently used and has various outdoor spaces (including exercise field, resting space, corridor, etc.), it was selected as the study object.

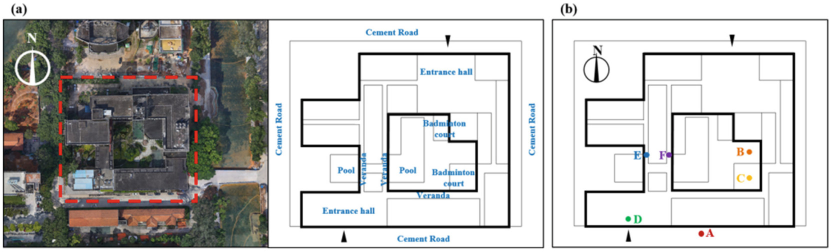

Fig. 1. (a) Aerial view of the building and layout of the first floor; (b) Locations of six measurement points.

2.2 Field Measurement

In order to analyze the thermal environment in outdoor spaces, six measurement points were selected according to their locations and surrounding conditions, as described in Sect. 2.1. The locations and detailed information of the six measurement points are indicated in Fig. 1(b) and Table 1 respectively.

Field measurement was conducted from 9:00 to 17:00 on a typical sunny day in the summer. Air temperature, mean radiant temperature (MRT) and wind speed at the six measurement points were monitored, and thermal images at the measurement points were captured by an infrared camera.

Table 1. Detailed information of the six measurement points.

Type	Point	Location	Surrounding condition
Outdoor	A	South sidewalk	No shading, concrete pavement
	B	Courtyard walking area	Trees shading, hard-tile pavement
	C	Badminton court	No shading, plastic-paved ground
Semi-outdoor (Transition space)	D	Entrance hall	Near concrete pavement, no trees
	E	West corridor	Near a pool
	F	East corridor	Near a pool

2.3 Numerical Simulation

Thermal improvement strategies for six outdoor spaces are proposed based on measurement results. Numerical simulation is used to quantify their improvement effects, which has advantages of accurate simulation results, low cost and without weather limitations. At present, there are some simulation tools for analyzing the thermal environment. A thermal simulation tool called ThermoRender is used for conducting this numerical analysis with consideration of outputting the surface temperature and MRT in the analyzed area. Its development principles and validation have been discussed in the previous study [11].

3 Results

3.1 Measurement Results

There was little difference of wind speeds at six measurement points, being around 0.8 m/s. On the contrary, variations of air temperatures and MRT at the six measurement points were obviously different, their hourly results are shown in Fig. 2 and Fig. 3. As seen in Fig. 2, the air temperatures in outdoor spaces (measurement points A, B and C) were higher than those in semi-open spaces (measurement points D, E and F). The same trend also appeared in the variations of MRT values, as seen in Fig. 3. In other words, the thermal environment in the outdoor spaces was hotter than in the semi-outdoor space. The main reason for this can be explained from the surrounding conditions around the six measurement points.

In the outdoor spaces (measurement points A, B and C), A and C are completely exposed to the sun, and their pavements absorb more solar heat. Therefore, uncomfortable thermal environments were formed at locations A and C. Due to shading from surrounding trees, air temperatures and MRT values at location B (outdoor space) were close to those in the semi-outdoor spaces.

In semi-outdoor space D, the shading area generated by upper sunshade was small, and both its ground and south road were paved with materials which are easy to absorb solar heat. Thus, the variation trends of air temperatures and MRT at point D were similar to that at point A. In addition, points E and F were in the space with long shading and near a pool, being relatively comfortable.

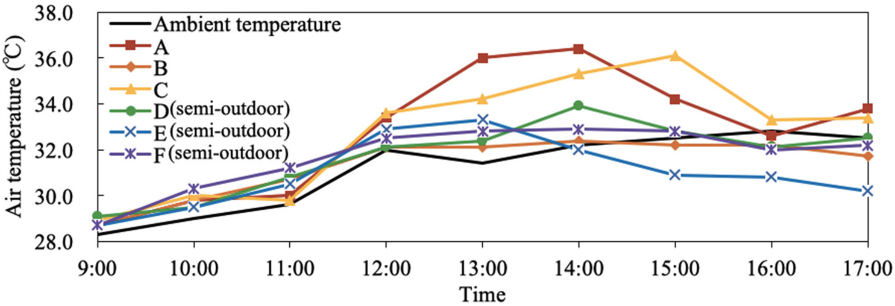

Fig. 2. Hourly variations of air temperatures at six measurement points.

Figure 4 presents thermography which was captured at 15:00. It can be seen that the surface temperatures of concrete pavement, building wall, plastic-paved ground and corridor ground were 50.2 °C, 39.4 °C, 50.8 °C and 38.5 °C, respectively. As shown in Fig. 4(b), the surface temperature of the hard tile under tree shading was 35.6 °C, more than 10 °C lower than that under sunlight. As a result, the surface temperature higher than the ambient temperature is the major cause for the formation of an uncomfortable thermal environment in the outdoor space.

The average air temperatures and MRT at the six measurement points were all higher than the ambient temperature by around 1 °C and 6 °C, respectively. It also can be found

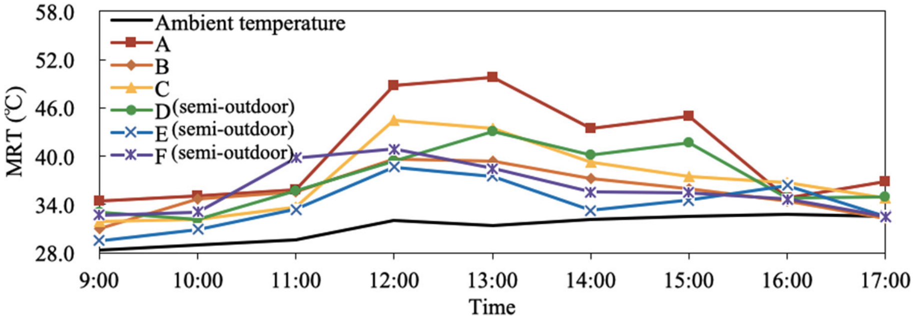

Fig. 3. Hourly variations of mean radiant temperatures at six measurement points.

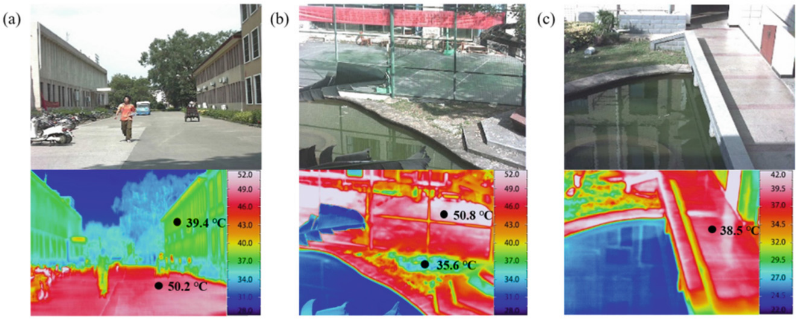

Fig. 4. Thermography captured at 15:00 in (a) location A (concrete pavement), (b) location C (badminton court), (c) location E (corridor).

that the surface temperature of the ground and building facades is the main factor affecting the thermal environment in outdoor and semi-outdoor spaces. Based on the above results, thermal improvement strategies are proposed for reducing the surface temperature in the analyzed area.

3.2 Thermal Improvement Strategies

Due to strong solar radiation and long summer in the hot-humid and less-windy climate, it is easy to increase surface temperatures in the analyzed outdoor space and form an uncomfortable thermal environment. There are some thermal improvement strategies for reducing surface temperature such as sunshade devices, planting trees and adding evaporative cooling equipment. The six measurement points covers different outdoor spaces including sidewalk, courtyard, badminton court, entrance hall and open corridor. Corresponding thermal improvement strategies were proposed based on the characteristics of these spaces.

Sidewalk (Point A). Trees are added along the sidewalks, which can provide shadow areas for pedestrians. And the original concrete pavement was replaced by permeable pavement to reduce the heat absorption, thereby decreased its surface temperature. Vertical greening was added on the building exterior walls near the sidewalks.

Courtyard (Point B). Tree-planting was selected to provide both shading and evaporative cooling. In order to reduce surface temperatures of the ground and facade, the hard title which was easy to absorb heat was replaced by permeable pavement and the exterior wall of the building was arranged with greening.

Badminton Court (Point C). It is difficult to change the paving material due to its use function. Shadow generated by surrounding trees and sun canopy can effectively reduce the exposure period of the badminton courts to the sun.

Entrance Hall (Point D). The main thermal improvement strategy is to extend the sunshade (cornice) above to enlarge the shading area. Trees were added on either side of the entrance hall to provide more shading and evaporative cooling.

Open Corridor (Points E and F). Horizontal sunshade devices were installed to reduce the effect of direct sunlight. For the open corridors on the east and west side, vertical sunshade devices were set up to reduce the influence of eastern and western sun exposure on its internal thermal environment. In addition, these sunshade devices were combined with water spraying, which could decrease the surface temperature of sunshade devices to a large extent.

3.3 Simulation Parameter Setting and Results

A thermal simulation tool (ThermoRender) [11] was used to calculate MRT distribution in the study area. Figure 5(a) is the 3D model of the study area. The same locations with the six measurement points were selected for simulation analysis. Meteorological data on a typical summer day in Nanning was used in the simulation, as shown in Fig. 5(b). The peak of outdoor air temperatures is above 33 °C. And the maximum intensity of solar radiation exceeds 800 W/m^2. Moreover, the average of wind speed is less than 1 m/s. Material parameters used in the simulation were set according to the actual condition. The evaporation of permeable pavement was set as 1.3 $kg/(m^2 \cdot d)$. In the simulation, the sunshade devices were maintained at the wet state by water spraying. This improvement strategy has obvious effect on humidity which is one of the factors affecting thermal comfort. However, this study neglected the humidity variation by water spraying with low intensity as much as possible.

Additionally, the width of the horizontal sunshade was set as 1.5 m, at a height of 3 m above the ground. The vertical sunshade was a shading grid with a size of 1×3 m (width × height) and its interval was 1 m. The sun canopy was 6 m above the ground. The height and crown diameter of the tree were all 6 m, and the tree-planting interval was 5 m.

MRT values at 1.5 m above the ground were used to analyze the improvement effect of the proposed strategies for the measurement locations. The comparison analysis of MRT variation between measurement results and simulation results was conducted before discussing the improvement effect. The results showed that there were different MRT variation trends among them. Nevertheless, the numerical simulation in this study aims to analyze the improvement effect of the proposed strategies by comparing simulation results with and without improvement strategies, the accuracy of simulation results is not discussed in this study.

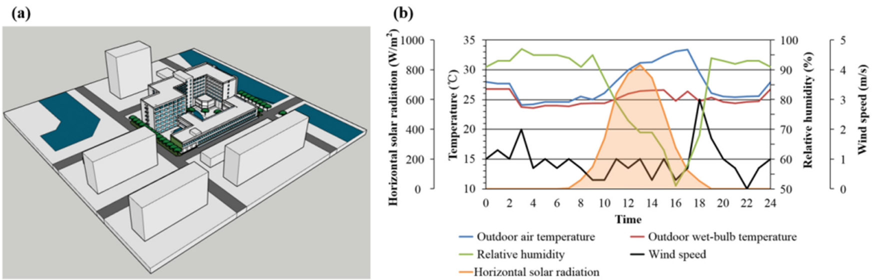

Fig. 5. (a) 3D model of the study area, (b) Meteorological data used in the simulation.

Hourly variations of MRT with and without improvement strategies are shown in Fig. 6. The average values of MRT from 9:00 to 15:00 for the six locations were used for comparison analysis, as shown in Table 2.

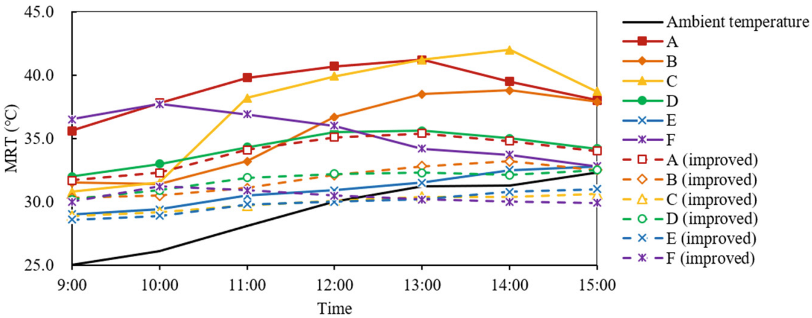

Fig. 6. Hourly variations of MRT in the six locations with and without improvement strategies.

In general, the thermal environment in the six locations has been effectively improved by the proposed strategies. The average MRT values in the sidewalk, courtyard, badminton court, entrance hall, west open corridor and east open corridor decreased by 5.0 °C, 3.6 °C, 7.6 °C, 2.5 °C, 1.0 °C and 5.1 °C, respectively. The maximum reduction of the MRT was found in the badminton court. The reason for this result was that the thermal environment was seriously hot before improvement, while the improvement effect of the sun canopy was obvious. The same improvement strategies were applied to the courtyard and sidewalk. The improvement effect was more obvious in the sidewalk due to more spaces for tree-planting. In the entrance hall, it is difficult to adopt more strategies due to the limitations of its location and function, thus the improvement effect was the least obvious. By comparing MRT reduction in the west open corridor and east open corridor, the sunshade was an effective measure to improve the thermal environment in the spaces exposed to solar radiation for a long time.

Various shading strategies were adopted in the targeted spaces, and the MRT reduction indicated their obvious improvement effects. Thus, reducing solar heat in these spaces is the most effective approach to improve outdoor thermal environment in the hot-humid and less-windy climate.

Table 2. Improvement effect (MRT reduction) after improvement in the six locations.

Analysis point	Location	Improvement strategy	Average MRT without improvement	MRT reduction
A	Sidewalk	Permeable pavement, trees, vertical greening of external wall	38.9 °C	5.0 °C
B	Courtyard	Permeable pavement, trees, vertical greening of external wall	35.4 °C	3.6 °C
C	Badminton court	Trees, sun canopy	37.5 °C	7.6 °C
D	Entrance hall	Sunshade extension, trees	34.2 °C	2.5 °C
E (West)	Open corridor	Horizontal and vertical sunshade, water spraying equipment	30.9 °C	1.0 °C
F (East)			35.4 °C	5.1 °C

4 Conclusion

This paper analyzed the outdoor thermal environment around an enclosed teaching building using field measurement data monitored in a hot-humid and less-windy climate. A simulation tool was used to quantify the effects of the proposed improvement strategies in the outdoor spaces. The main conclusions in this study are summarized as follows:

(a) The summertime thermal environment in the measured outdoor spaces was severe, and their average air temperatures and MRT were higher than the ambient temperature by about 1 °C and 6 °C, respectively.
(b) In the study area with hot-humid and less-windy climate, the surface temperature is the main factor affecting the formation of the thermal environment in outdoor and semi-outdoor spaces. The improvement strategies for reducing the surface temperatures in the measured spaces were proposed, including sunshade devices, greening and water spray cooling.
(c) The proposed improvement strategies effectively improved the thermal environment in the outdoor spaces, and the MRT value can be reduced by 1.0 °C to 5.1 °C on average.
(d) Solar shading is the most effective approach to improve summertime outdoor thermal environment in the hot-humid and less-windy climate.

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