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Thermal Performance of Vertical Courtyard System in Office Buildings Under Typical Hot Days in Hot-humid Climate Area: A Case Study

Jin Wei [1], Fangsi Yu [2], Haixiu Liang [1,*] and Maohui Luo [3,*]

[1] School of Architecture, South China University of Technology, No.381 Wushan Road, Guangzhou 510640, China; arjin.wei2013@mail.scut.edu.cn
[2] School of Architecture & Environment, College of Design, University of Oregon, OR 97403, USA; yufangsi2012@gmail.com
[3] Center for Built Environment, University of California Berkeley, Wurster Hall, Berkeley, CA 94720, USA
* Correspondence: lianghaixiu@scut.edu.cn (H.L.); lmhtongji@berkeley.edu (M.L.)

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Abstract: Due to the different types of courtyards in vertical courtyard system (VCS), their impacts on thermal performance in office buildings may vary. To better understand this issue, this paper investigates the thermal performance impact of three typical vertical courtyards. A field case study was conducted in VCSs during two typical extreme hot days under hot-humid climate conditions. The results show that the vertical courtyards have significant cooling effects under hot-humid climatic conditions. Via testing on linear, integrated, and rooftop courtyard with fusion layout, the fusion one has an obviously positive impact on air temperature reduction (4.3 ºC). Compared with the linear and integrated courtyards, the maximum air temperature difference of fusion layout is around 1.6 ºC. The thermal radiation environment of the fusion layout was better than that of the other two (linear and integrated). Besides, the surface temperature of the pavements (wood panel) in the vertical courtyards can reach 47 ºC, while the vegetation can lower it by 8 ºC under the same weather conditions. These findings show that the courtyard with fusion layout is more suitable for extreme hot weather conditions.

Keywords: vertical courtyard system; thermal conditions; cooling effect; hot-humid climate; field measurement

1. Introduction

Due to the rapid population growth and shortage of urban land, a large amount of natural urban green space in China has been replaced by concrete constructions with a low surface reflectivity [1–3]. In order to improve the efficiency of land use in urban areas, high-rise and high-density buildings are continually being built. This causes several environmental issues, among which the urban heat island effect (UHIE) and increased heat-related morbidity and mortality under extreme heat conditions have attracted much attention, especially in hot-humid areas [4–6]. To mitigate these issues, practical solutions in urban construction are urgently needed. Among them, implanting vertical courtyard system (VCS) into high-density buildings has been a promising approach, as shown in Figure 1. This trend is more obvious in hot-humid climate areas. As reported by Aldawoud [7], courtyards can result in significant temperature reductions, but their impacts will vary with environmental factors, such as climate conditions, ambient surface properties, and courtyard forms.

From the architectural perspective, the courtyard refers to an enclosed outdoor or semi-outdoor yard space [8]. Vertical courtyard is built upon artificially elevated urban surfaces but is characterized by environmental and spatial quality similar to those on the ground. Generally, the vertical courtyard can be interpreted in two ways. First, it is a comprehensive node with multifunction, including spaces for rest, circulation, landscape, and other uses, not just green space with vegetation. Second, the vertical courtyard connects various vertical layers and contains a complete spatial form in the vertical direction of a building, not just like horizontal courtyard space [9,10].

Breaking the connection between intensive buildings and their surrounding environment may cause excessive energy consumption and the UHI issue [11,12]. The VCS helps construct a climate buffer in the atmosphere, which reduces temperature and guides natural ventilation into buildings. This consequently improves the indoor thermal environment and reduces air-conditioning energy consumption [13]. Therefore, the courtyard system has been considered a key solution that integrates regional micro-climatic characteristics to overcome the challenges in the high-rises and high-density environment [14].

VCS can be classified in different ways [15–17]. Normally, VCS is defined based on the courtyard' spatial relationship with the main functional space and the core cube from the perspective of architectural space. These are six common VCS categories: attached, semi-enveloped, integrated, linear, and rooftop courtyard (fusion—layout with more than two types of vertical courtyards) (as illustrated in Table 1). The VCS is also considered as a flexible and expandable space at the intersection of the functional modules of office buildings which provides the possibility of functional transformation and expansion [18,19]. Hertzberger [20] put forward the Variable Space that corresponds to "flexibility", which suggests that spatial characteristics possess the adaptive capacity based on the needs over time. Additionally, Kurokawa [21] proposed the "Intermediary Space theory", holding an opinion that inner space can integrate opposite objects in a dynamic and vibrant symbiosis.

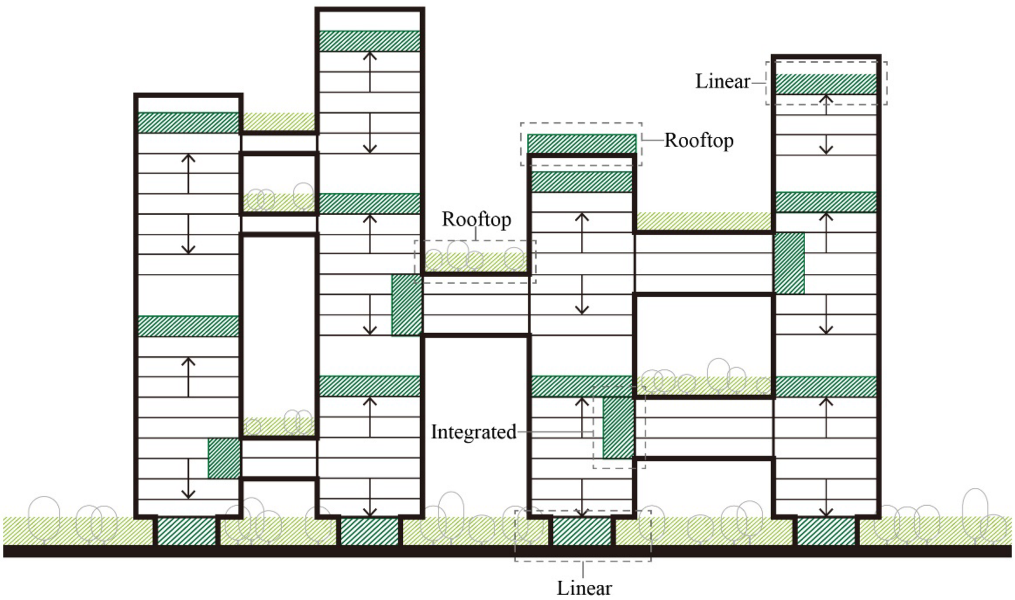
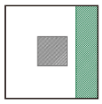
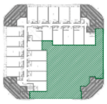
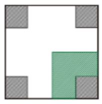
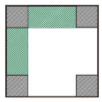
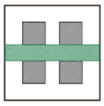
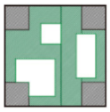


Figure 1. The secondary ground of the urban high-density area.

The contribution of this paper can be summarized as three folds. First, this paper investigated three typical types (linear, integrated, and rooftop with fusion layout) of vertical courtyards in a typical high-density office building and found its different cooling effects during extremely hot days under hot-humid climatic conditions. Previous studies mostly focused on the vertical greenery system (VGS) and did not describe the environmental characteristics from the perspective of architectural space. Second, this paper estimated the thermal control impact of different vertical courtyards, supporting the better thermal performance of the rooftop courtyard with fusion layout under hot-humid climate condition. Third, this paper compared the thermal radiant environment of two typical vertical courtyards and rooftop courtyard, combining the surface materials and spatial structure, and found that the open and permeable rooftop courtyard is better than that of the other two (linear and integrated) in VCS.

Table 1. Common VCS types and their features.

Type	Typical Pattern	Example	Description	Type Diagram	Legend
Attached		Cd De Mexico Santa Fe, Mexico	Three sides contact with the external environment		
Semi-envelope		Oasia Hotel Novena, Singapore	Two adjacent sides contact with the external environment		core cube 
Integrated		Commerzbank Tower, Frankfurt am Main, German	One side contacts with the external environment		courtyard 
Linear		Baidu International Building, Shenzhen, China	Two opposite sides contact with the external environment		functional space 
Rooftop Courtyard (fusion)		NanguoYiyuan, Nanning, China	Outdoor courtyard on the roof (with functional space)		

This paper is organized as follows: Section 2 reviews related literature and summarizes benefits of VCS, Section 3 introduces the study methods and describes the field measurement, Section 4 presents the results and detailed discussions, and Section 5 concludes the major findings.

2. Benefits of Vertical Courtyards

2.1. Urban Microclimate and UHIE

Detailed studies on the interaction of local climates and urban development provide analyses and insights into the characteristics of individual cities. Urban microclimate refers to the characteristics of climate in the Urban Canopy Layer (UCL) between the buildings' rooftops and the ground [22,23]. A more prominent problem is the UHIE of UCL. Common green space on the ground level is ineffective for high-rise and high-density areas [24]. Recent studies [25–27] show that the courtyard is often considered as a microclimate modifier that improves the comfort level of the surrounding environment and helps mitigate UHIE. The measurements of the ambient temperature and relative humidity from the study of Pérez et al. [28] also support that the courtyard in high-rise buildings creates a microclimate characterized by lower temperature and higher humidity. Similar results are also reported by Ghaffarianhoseini et al. [29], in which the rooftop vegetated courtyard acted as a tool that improved the comfort level by modifying the microclimate around the building and enhancing the ventilation.

2.2. Benefit in Thermal Environment

A large number of publications can be found on the urban greenery system focusing on the impact of vegetation on the buildings and emphasizing the vegetated elements rather than architectural space-oriented VCS. Many studies report that the vegetated-oriented courtyard is highly efficient in decreasing air temperature. Rajapaksha et al. [30] show a strong correlation between the wall surface temperature and indoor air temperature and argue that indoor air temperature is significantly affected by solar radiation received by the enclosing wall. Balaras [31] states that the courtyard can attenuate heat ingress into interior space and control its diurnal temperature amplitude. The higher the temperature difference is, the more unstable the indoor thermal environment is, because it is more easily influenced by the outdoor environment [32]. Additionally, the vertical courtyard's ability to provide sufficient natural ventilation and form maximized airflow is demonstrated by CFD analysis and wind tunnel experiments. Sharples and Bensalem [33] illustrate the way in which airflow patterns form after the courtyard's implantation. The courtyard can help to create a comfortable indoor environment as an environmentally friendly way of temperature regulation [34].

2.3. Energy Efficiency

Saving air conditioning energy is another benefit of VCS [35,36]. Studies on low energy consumption and ecological courtyard space have attracted the attention of researchers. In tropical and subtropical areas, most energy in high-rise buildings is consumed by thermal environment conditioning. Heating, ventilation, and air-conditioning (HVAC) consumed over 50% of the total energy consumption in high-rise buildings [37–39]. Aldawoud [7] reveals that courtyards are more energy efficient in hot climate areas than in temperate or cold climate areas. At the same time, the vegetated courtyard is widely adopted in the high-rises in tropical and subtropical environment [40]. Aldawoud and Clark [41] show that the courtyard is more common in the high-rise building than low-rise one in Miami. Other studies show that incorporating courtyards into buildings can be considered as one of the daylight-enhancing techniques to minimize space conditioning and lighting loads [42–44].

3. Materials and Methods

3.1. Field Measurements

Field measurements were conducted to evaluate the thermal effects of the VCS through thermal-related parameters. Our group did further study on typical hot days [45]. The measurements were conducted in the VCS of a high-density office building at Nanning City, located in the hot-humid climate zone. Its summer season lasts over six months. As shown in Figure 2, the maximum daily outdoor temperature in summer is above 30 °C, the relative humidity is around 80%, and the average monthly rainfall is as high as 200 mm. The statistics above indicate that the main climatic characteristics in Nanning City are hot and rainy during summer.

The tested VCS in the target building mainly contains three types of the vertical courtyards, which include linear (first floor), integrated (third floor), and rooftop (seventh floor) courtyard with fusion layout (shown in Figure 3). The testing points were conducted on sitting areas with highest utilization rate and closely related to occupants, through continuous observation in two typical hot days in the summer. The selection of these points aims to evaluate the cooling effects of different types of vertical courtyards.

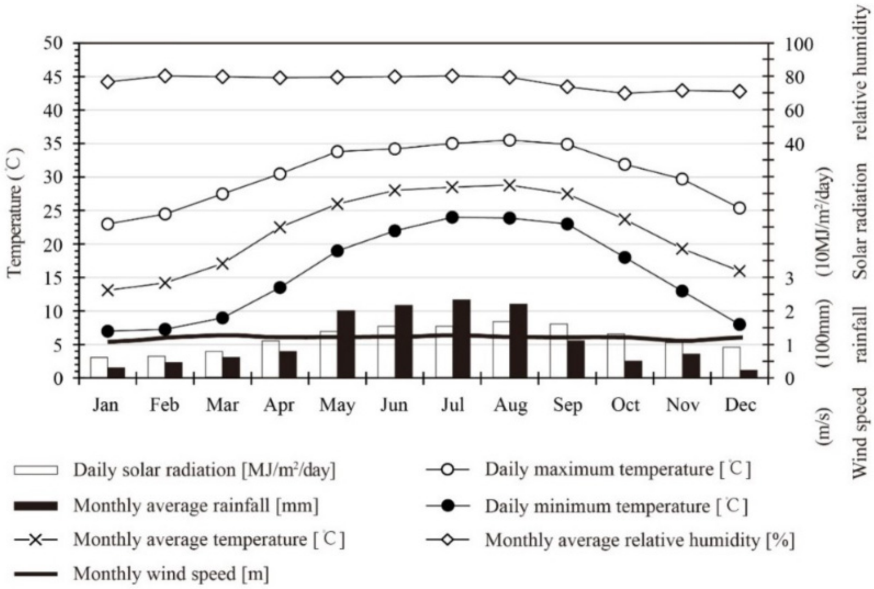


Figure 2. Nanning climatic context.

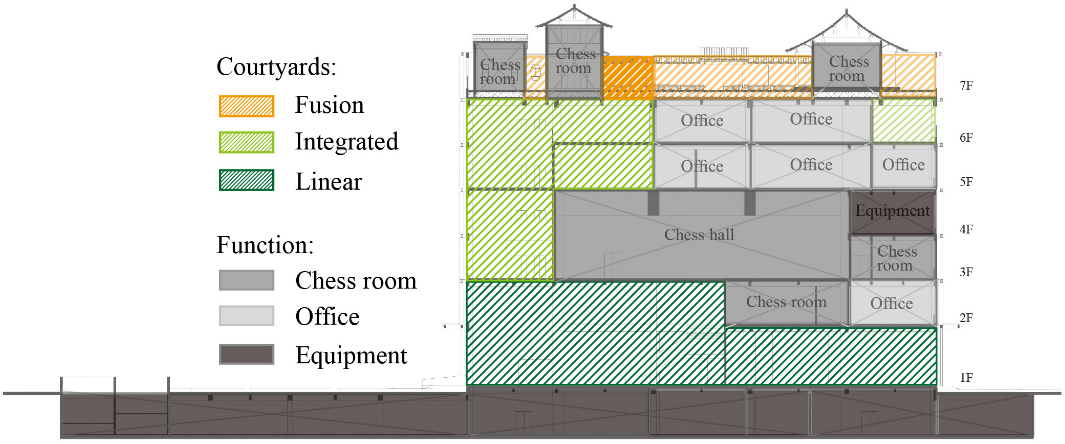


Figure 3. Distribution of tested courtyards.

3.2. Weather Cduring the Field Measurements

The filed test was taken on typical hot days with high temperatures and high humidity. Figure 4 shows the continuous measurements on air temperature, relative humidity, and horizontal solar radiation in three days, which were recorded by weather station located in Guangxi University (the distance between the campus and targeted object are more than 10 km). The day before the first day (day 0) was a sunny day, and the value of the total horizontal solar radiation exceeded 400W/m² from 12:00 to 14:00. During the experiment, the daily highest air temperature was 34 °C appearing at 13:00 to 15:00, and the average air temperature exceeded 30 °C (under extreme hot conditions) from 12:00 to 16:00. Moreover, the numerical fluctuation range of relative humidity was from 50% to 95%. Without any mitigation solutions, people will feel stuffy in such weather conditions [46].

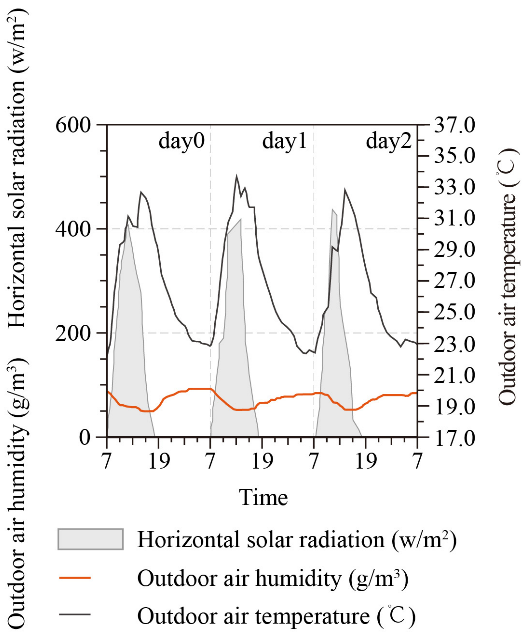


Figure 4. Outdoor temperature, humidity, and total horizontal solar radiation recorded during the test.

3.3. Instrument and Measured Parameters

The following parameters were measured at each location with a measuring height of 1.2 m above the ground. More detailed information on related parameters are listed in Table 2. The sensors were mounted on tripods which were located in semi-outdoor space, as shown in Figure 5. The globe temperature was measured by the standard globe temperature probe [47]. It is worth explaining that the wind speed of each floor (first, third, and seventh) had two measuring points: one was close to the south-oriented side (one person held a hot-wire anemometer poking their hands out of the courtyard) and the other was standing on the center of the courtyard (second point). The difference between the two points in each floor indicates the ventilation effect of vertical courtyard in each floor. The data of wind speed was obtained from 12:00 to 16:00 with measuring every 15 minutes. Besides, the surface temperature was obtained using an infrared camera through mobile test from 13:00 to 14:00.

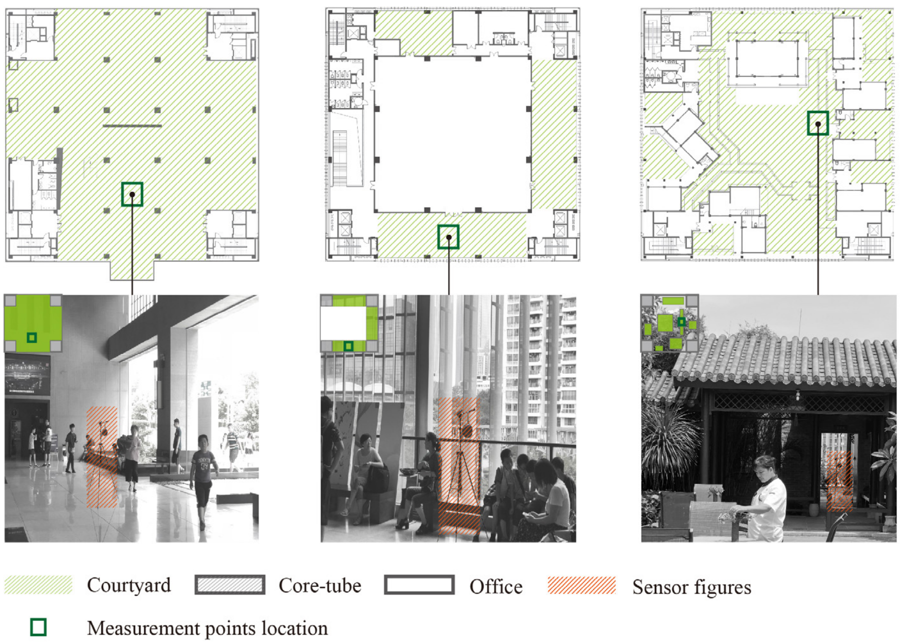


Figure 5. View measurement locations and parameters.

Table 2. Description of measurement parameters and sensors.

Measurement Parameter	Sensor Type	Accuracy	Frequency	Note	Figure
Air temperature	HOBO temperature data logger	± 0.5 °C	5min	--	
Relative humidity	HOBO humidity data logger	3.0%	5min	--	
Air velocity	Hot-wire anemometer	± 0.1 m/s	15min (12:00–16:00)	Portable instrument	
Globe temperature	Standard globe temperature probe	± 0.15 °C	20min		
Surface temperature	Infrared camera	± 0.2 °C	(13:00–14:00)	--	

3.4. Details Description of Measuring Points

The targeted building is located in the high-density core area of Nanning city and is surrounded by high-rise buildings (the bottom middle of Figure 4). As seen in Figure 3, the tested office building has a highly dense form with diverse functional space, not just office space. With further description, the bottom space of the building is a kind of linear courtyard and part of it is across a height of two floors. The integrated courtyards are applied in interlayers (third to sixth floor). The rooftop has some functional space with a free-style layout, not just the greenery space with vegetation. The lawn coverage on the pavement of seventh floor is 10%, and the wood panel coverage reaches 90% as a preliminary estimate during measurement. Besides, the parameters of materials and structures for pavements and exterior walls are listed by checking statistics from the Chinese building material specifications and field survey results, as seen in Table 3.

Table 3. The components of exterior materials (pavements and exterior walls).

Components	Coverage	Thickness of Materials (mm)	Thermal Conductivity (W/mk)	Specific Heat Capacity (kJ/m^3.k)	Reflectivity (%)
Pavements					
(1st linear)	Ceramic tile (light color) (100%)	Ceramic tile (10)	3.49	2576	30.0
		cement mortar (50)	0.93	1890	
		gravel (200)	1.28	1932	
		compacted clay (400)	1.16	2020	
(3rd integrated)	Ceramic tile (light color) (100%)	ceramic tile (10)	3.49	2576	30.0
		cement mortar (50)	0.93	1890	
		gravel (200)	1.28	1932	
		compacted clay (400)	1.16	2020	
(7th rooftop)	Wood panel (90%)	Wood panel (20)	0.35	1720	20.0
		gravel (200)	1.28	1932	
		compacted clay (400)	1.16	2020	
Exterior walls					
(1st linear)	Ceramic tile (light color) (40%)	Ceramic tile (10)	3.49	2576	30.0
		cement mortar (50)	0.93	1890	
		gravel (200)	1.28	1932	
		compacted clay (400)	1.16	2020	
(3rd integrated)	Ceramic tile (light color) (40%)	Ceramic tile (10)	3.49	2576	30.0
		cement mortar (50)	0.93	1890	
		gravel (200)	1.28	1932	
		compacted clay (400)	1.16	2020	
(7th rooftop)	Glass (10%)	glass (8)	0.76	2100	12.6
	Wood panel (20%)	Wood panel (20)	0.35	1720	20.0
		gravel (200)	1.28	1932	
		compacted clay (400)	1.16	2020	

4. Results and Discussions

4.1. Wind Velocity

Comfortable ventilation not only brings cool air in, but also increases air movement, which has equivalent effects of temperature reduction [48]. Through wind velocity measurement in courtyard space, the natural ventilation performance of different vertical courtyards can be compared. Figure 6 shows the wind speed of three points measured from 12:00 to 16:00 (measuring every 15 minutes).

Three different scatter points in Figure 6 show the differences between outdoor and indoor wind velocity of each vertical courtyard (first, third, and seventh). The scatters also indicate the range of wind velocity of each courtyard. As seen, the range of three types of outdoor wind speed was close, while that of indoor wind speed had greater difference between integrated courtyard and the other two (linear and rooftop). The indoor wind of integrated courtyard was smaller (0.25m/s to 1.15m/s) than that of the other two. With further observation, the range of courtyard wind speed of linear and rooftop one was larger than that of integrated one, with more scatters appearing in relatively high-speed range (0.8m/s–1.4m/s).

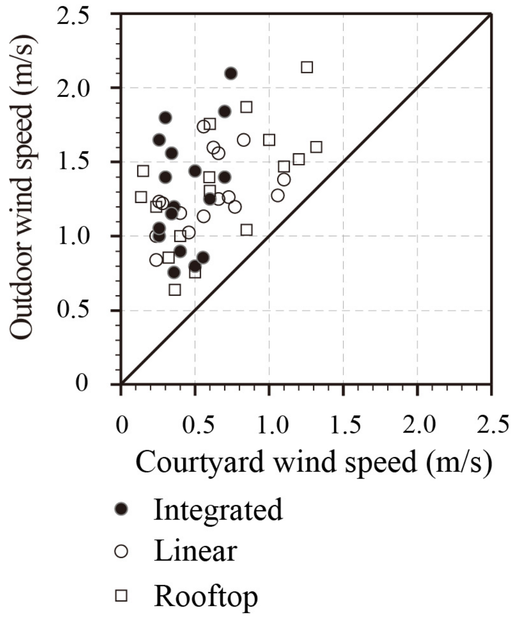


Figure 6. Scatter gram of wind velocity in the daytime period.

4.2. Air Temperature and Relative Humidity

The measured air temperatures of different points during the test period are shown in Figure 7. The outdoor air temperature (day 1) from 12:00 to 18:00 exceeded 30 °C, representing a typical extremely hot day in Nanning. The results also show that the highest air temperature (peak value) obtained from Point 1-S was 30.3 °C, and the peak value of Point 7-S was 28.7 °C when the outdoor air temperature was 33 °C. Similar air temperature was obtained at Point 3-S with the peak value of 30.3 °C during the typical hot days. Figure 8 shows the relative humidity during two consecutive hot days. As seen, the relative humidity is approximately inversely proportional to air temperature. The higher the air temperature is, the lower relative humidity is.

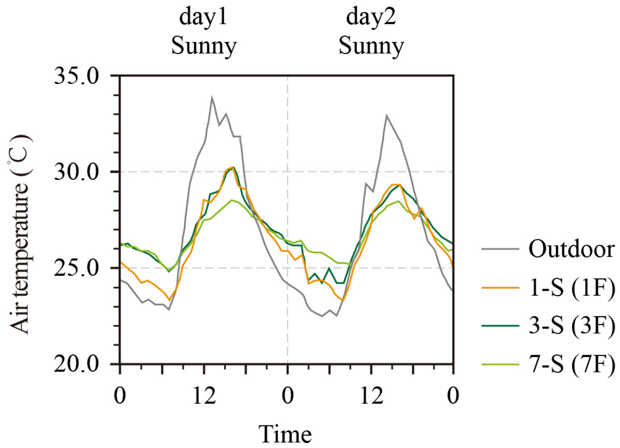


Figure 7. Measurement results of air temperatures during two consecutive days of testing.

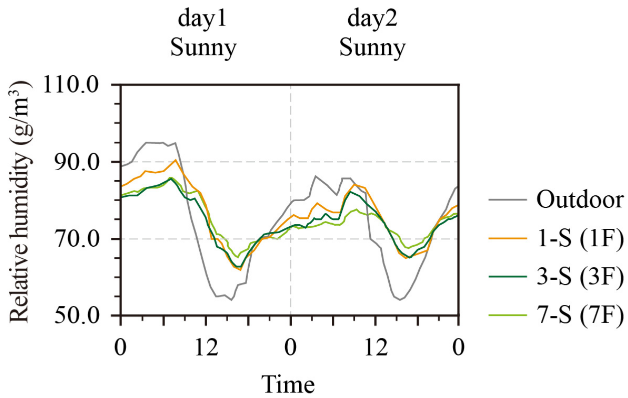


Figure 8. Measurement results of relative humidity during two consecutive days of testing.

4.3. Surface Temperature and Thermal Radiation

Figure 9 shows surface temperatures surrounding the measurement locations (Point 1-S, 3-S, and 7-S) in the daytime from 13:00 to 14:00 on day 1. It indicates that notable reductions in surface temperatures are achieved by the vertical courtyards. As the thermal environment of the VCS is influenced by its surroundings, it is necessary to consider the interactions between the semi-outdoor and outdoor thermal environments [27].

Point 1-S locates in a linear courtyard, where the temperature of shaded surface (including the underlying surface) was 33 °C at 13:06 (see the thermography of Figure 9a). At this time, the ambient surrounding outdoor surface temperature were above 43 °C. The thermography of Figure 9b was taken in a south-oriented integrated courtyard at location 3-S. The side sunshade made of membrane materials was warmed up to above 43 °C due to solar radiation, whereas the surface temperature of the pavement was around 34 °C. The third thermography (Figure 9c) was taken on the rooftop courtyard at Point 7-S, and Figure 9d showed the surrounding environment of Point 7-S. The ground surface temperature with pavement (wood panel) on the shaded pedestrian passage was around 34 °C, whereas the outdoor surface (tile) temperatures were above 47 °C. The difference between unshaded ordinary pavement (47 °C) and unshaded vegetation (39 °C) was around 8 °C.

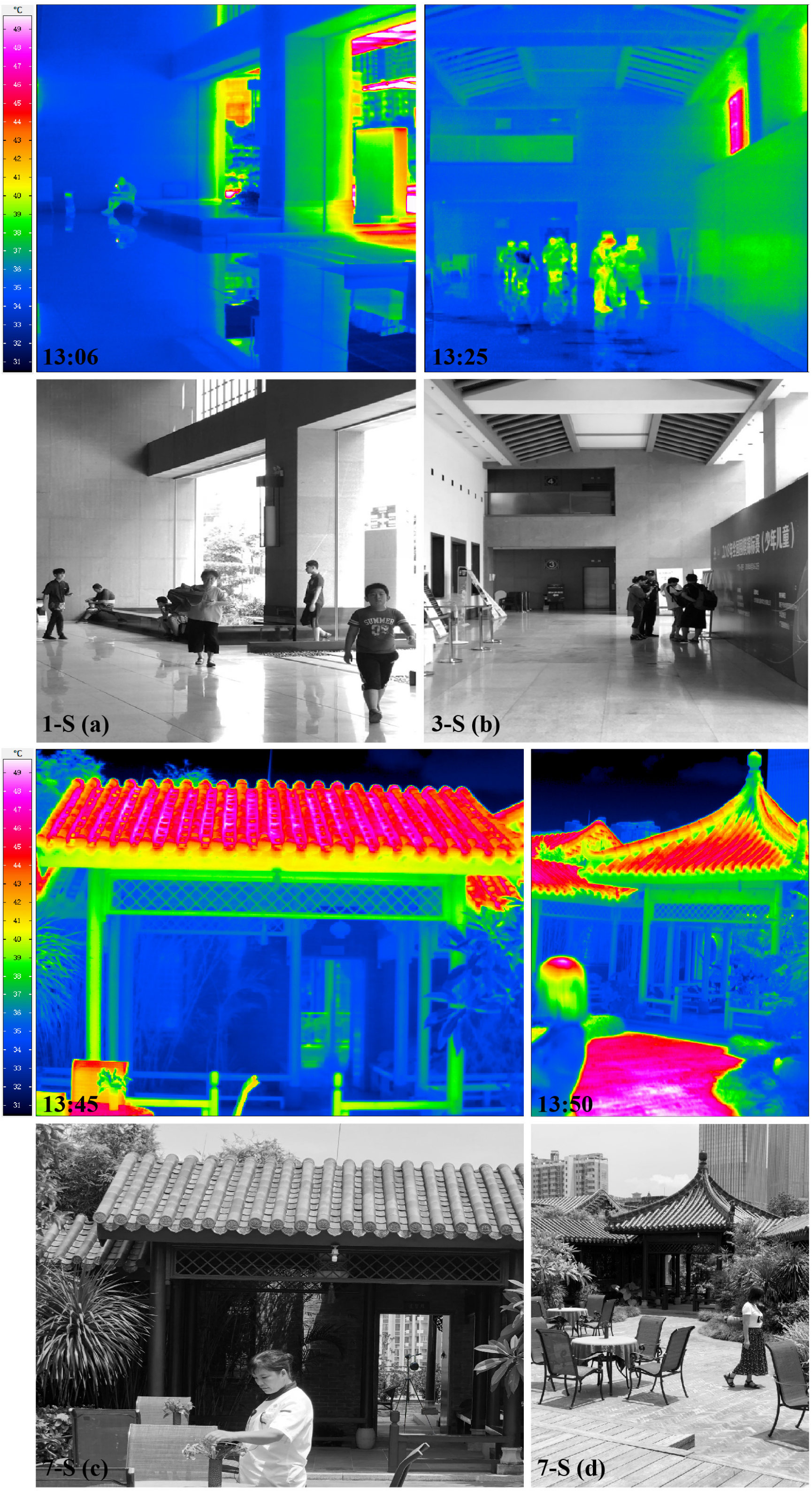


Figure 9. (**a**) Thermograph and visual photo of Point 1-S taken at 13:06. (**b**) Thermograph and visual photo of Point 3-S taken at 13:25. (**c**) Thermograph and visual photo of Point 7-S taken at 13:45. (**d**) Thermograph and visual photo around Point 7-S taken at 13:50.

4.4. Air Temperatures and Globe Temperatures

Figure 10 shows the relationship between global temperatures and air temperatures during daytime and nighttime, respectively. The differences between globe temperatures and air temperatures reflect thermal radiation environments. As seen in Figure 10b, the globe temperatures at Point 1-S and Point 3-S were all higher than those at Point 7-S, when the air temperature was the same during nighttime. As seen, most points measured from Point 7-S were closer (than Point 1-S and Point 3-S) to 45 °C diagonal line, reflecting better thermal radiation environment without solar radiation. As seen in Figure 10a, most globe temperatures on measured Point 7-S were lower than those of the other two, when the air temperature was lower than 28 °C during daytime. The fluctuation of globe temperatures at Point 7-S was obvious than those of the other two, when the air temperature exceeded 28 °C. The results indicate that the increase of globe temperature at Point 7-S was impacted by the pavement of surrounding outdoor square absorbing solar radiation during daytime (as seen in Figure 9d).

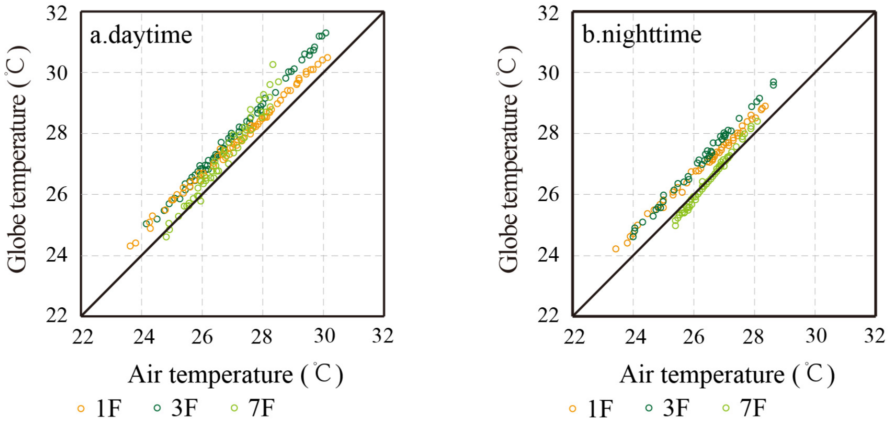


Figure 10. (**a**) Scatter diagram of globe temperatures—air temperatures during daytime. (**b**) Scatter diagram of globe temperatures—air temperatures during nighttime.

4.5. Discussion

Based on the results shown in Figures 6–10, some interesting findings can be summarized as follows:

First, during the test, all the measured vertical courtyards showed remarkable cooling effects on air temperatures on extremely hot days. For the rooftop with fusion layout, integrated, and linear courtyards, more than 4.3 °C, 2.7 °C, and 2.7 °C temperature reduction can be obtained under sunny days. Obviously, the rooftop courtyard with fusion layout achieved better insulation characteristics and maximum temperatures reduction than the other two courtyards. The rooftop courtyard with fusion layout is also one of the most common ventilating spaces with the smallest difference in outdoor and indoor wind speed in this targeted VCS (as shown in Figure 6).

The magnitude of temperature differences between courtyards is noticeable on extremely hot days and the maximum difference reaches 1.6 °C (between Point 1-S and 7-S), occurring at the hour of 15:30 on day 1. Obvious air temperature reduction in Point 7-S can be explained by sun-shading from gray space and the flexible fusion layout for promoting the wind speed, while the range of wind speed in rooftop is larger than that of the other two courtyards. On the other hand, similar thermal insulation performance is observed from Point 1-S and 3-S with the same surface material under extreme hot conditions. Compared to Point 1-S, Point 3-S has better temperature mitigation effects from the measuring on air temperature. This is the similar results with that Hussain and Oosthuizen [49] got.

Second, the temperatures of the shaded surfaces are far below bare outdoor surface temperatures. In the VCS, the maximum difference of wall surface temperature between shaded and unshaded reached 11 °C. However, in the hot-humid area, the application of materials of pavements, and exterior walls are worth consideration. As seen in Figure 9c,d, the surface temperature of pavement (wood panel) in rooftop reaches 47 °C under high solar radiation during noon, for the sake of the low reflectivity (20%).

From the in-situ test, the surface temperature affects the surrounding air temperature. The south-oriented outdoor unshaded passage is irradiated by solar radiation at the afternoon hour where a hot environment is formed. The hot surrounding environment has negative impacts on courtyard's thermal environment [50]. These visual images of spatial environment show a comparison of different kinds of vertical courtyards and makes it easier to understand the thermal control impact of VCS.

Third, differences between globe temperatures and air temperatures show how vertical courtyards are impacted by surrounding thermal radiation. Compared to Point 7-S, the thermal environment of Point 1-S and Point 3-S were further affected by thermal radiation from the surrounding environment. Besides, it can also be concluded from Figure 10 that the black-bulb thermometers located in Point 1-S and Point 3-S were sheltered to some degree, and the effect of nighttime heat dissipation with long-wave dropped significantly, which can be a possible reason why the globe temperatures (not exposed to the sun during the nighttime) were higher than air temperatures. Compared to Point 3-S, the average difference of global temperature and air temperature of Point 1-S is smaller, as well as the fluctuation in the range of high temperatures. Combing the ventilation performance, it can be indicated that the thermal radiation environment of the linear courtyard (Point 1-S) is relatively better than that of the integrated courtyard (Point 3-S).

Lastly, the temperatures of the shaded surfaces are far below the relevant outdoor surface temperatures. The maximum surface temperature difference of outdoor pavement (wood panel) between shaded and unshaded reached 13 °C, while the difference of surface temperature between shaded (33 °C) and unshaded (38 °C) lawn is 5 °C. The surface temperature of the unshaded lawn is around 8 °C lower than unshaded ordinary pavements. The ranking of surface temperature difference is that hard pavement (exposed to sunlight) > hard pavement (shaded) > lawn (shaded).

Technical measurements to reduce excessive surface temperatures on pavements should be considered. Permeable paving materials, such as sintered ceramic porous brick (CB) and open-graded pervious concrete (PC) are effective in decreasing the temperature and alleviating hot environment.

VCS is not only visually appealing in a high-rise building, but also has the benefits in creating comfortable outdoor and indoor environments, mitigating building conditioning energy consumption and reducing carbon emissions [51,52]. In hot-humid climatic areas, an obvious reduction on the cooling load appears in buildings with high-volume occupants [53]. This shows environmental sustainability of VCS implantation to tensely functional space. The courtyards which can be implemented in VCS are not limited to the linear, integrated, and rooftop categories. Other types like semi-enveloped and fusion style are also very promising.

5. Conclusions and Policy Implication

By taking an in-depth look at VCS in office buildings with high-density functional space, different types of vertical courtyards in a hot-humid area were experimentally investigated in terms of thermal control performance. Filed investigations were conducted under extreme hot condition. The main findings are as follows:

First, vertical courtyards have significant cooling effects on the basis of the spatial structure (form) under hot-humid climatic conditions.

Second, rooftop courtyard with fusion layout is more suitable for the hot-humid climate zone for its flexible functional space and better cooling effect. Under extreme heat conditions, air temperatures reduction from linear, integrated, and rooftop courtyards are 2.7 °C, 2.7 °C, and 4.3 °C, respectively.

Third, the thermal radiation environment of permeable rooftop courtyard might be better than those of the other two (linear and integrated).

Lastly, the surface temperature of the pavements (wood panel) in the vertical courtyards can reach 47 °C. Technical measurements should be taken to reduce the excessive surface temperature on pavements. For instance, the surface temperature of the pavement with vegetation-planting is 8 °C lower than that of ordinary pavements under the sunlight.

The conclusions above have noteworthy implications for policymakers and practitioners. First, thermal performance of courtyard space is an important indicator to be considered for the design of office buildings in hot-humid climate zones. When making a new method and demonstration of regional climate adaptation for the design of the green buildings, the government is supposed to consider not only energy conservation caused by energy efficiency improvements, but also environmental adaptation, such as the forms, materials, culture, and spirit under different geographical conditions.

Second, when pursuing increases in the construction of high-rises, or super high-rises in an urban high-density area, building operating efficiency policy implementation can be inclined to developed regions, where buildings and surroundings have large interactions and the impact of outdoor thermal environment on building operating efficiency improvement tend to be more effective for energy conservation.

Third, the improvement of the thermal performance of vertical courtyards with high-volume occupants should be widely aware, especially under high temperature and high-humidity climatic conditions. This study provides empirical evidence for architects to consider the impact of different VCSs on the thermal performance in high-density environment by adjusting the spatial forms and constructed surface materials.

In the future, further research on this topic is needed to be produced. For instance, we can evaluate and predict the thermal improvement effect of VCS and investigate how it changes under different climate conditions. Moreover, further explorations are needed to correlate the VCS's thermal effects and energy consumption of office buildings in high-density environments.

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