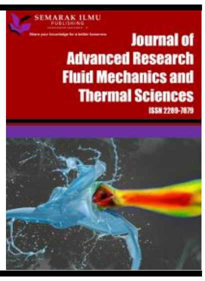
SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Assessment of Ventilation Performance and Thermal Comfort in Semi-open Spaces of Naturally Ventilated Traditional Dwellings in Tai Lake Area, China

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ARTICLE INFO

Article history:
Received 16 July 2024
Received in revised form 25 October 2024
Accepted 6 November 2024
Available online 20 November 2024

Keywords:
Semi-open space; natural ventilation; traditional dwelling; thermal comfort

ABSTRACT

Semi-open space is a special architectural space form between indoor and outdoor, which has the functions of transition, climate regulation and energy saving. Effective use of semi-open space is an important ecological strategy in adapting to the climatic conditions of traditional dwellings in Tai Lake region of China. However, it has been shown that the hot and humid summers in the area caused discomfort for a large number of urban dwellers. Therefore, in this research, field measurements based on four environmental parameters (Ta, Tr, Va and RH) were conducted from 27 June 2023 to 7 July 2023 in three multi-courtyard traditional dwellings in the Tai Lake area to evaluate the ventilation performance and thermal comfort of the interior and semi-open spaces of the dwellings. The aim was to assess the role of semi-open space types and structures in the climate regulation of architectural spaces and their potential application in the design of modern dwellings to reduce summer discomfort. Semi-open spaces are effective in promoting natural ventilation to cool the building. This cooling effect is not due to the semi-open spaces themselves having lower temperatures. The indoor thermal environment was influenced by the outdoor climate and had a lagging effect. In addition, the ventilation performance of the semi-open space inside alley was the best, followed by the patio closest to the door.

1. Introduction

Global energy shortages and high energy consumption in buildings have led to an increasing focus on low and zero energy passive building energy efficiency technologies. According to IEA [1], global energy generation will increase from 123% to 150% by 2050 if current trends continue. China's building and construction energy consumption, which accounted for 45.5% of the country's total energy consumption in 2020, will continue to rise in the future. The annual electricity consumption of Chinese rural residents for domestic use had increased from 6,311 million kWh in 1980 to 639.7

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https://doi.org/10.37934/arfmts.124.1.160182

billion kWh in 2020, which was a 100-fold increase. This suggests that there is a huge demand and opportunity for energy efficiency measures in rural residential buildings in China, and that environmental sustainability can be achieved through the implementation of energy efficiency programmes and use of clean energy. Natural ventilation, which utilises natural energy sources such as wind and avoids the use of polluting energy sources, is an effective solution for achieving building sustainability [2].

Traditional dwellings are buildings adapted to different regional climates, built by using simple construction means under historical conditions of limited resources and technology [3]. The climate-adapted construction methods of traditional dwellings are still relevant today. However, as living standards have improved, many people have begun to use mechanical methods such as air conditioning and heating, which has increased energy consumption. In order to reduce energy consumption and meet thermal comfort needs, it is necessary to discover and optimise the natural ventilation methods of traditional dwellings for application in modern buildings [4]. It was found that traditional dwellings in the Tai Lake area had effectively improved the thermal environment in hot and humid climates through natural ventilation techniques in semi-open spaces. Semi-open space is a special form of architectural space that exists between indoor and outdoor, and is a transitional space that connects spaces of different natures, for example, the "grey space" in architecture [5]. It plays an important role in transition, climate regulation and energy conservation, enhancing the living environment and air quality, buffering climate change and bringing about low energy consumption [6].

Passive design, such as natural ventilation, is an effective strategy for reducing energy consumption in buildings and an essential design factor for traditional dwellings to cope with the climate [7]. Researchers have learnt from traditional buildings to improve energy efficiency [8-11]. In the Sub-Saharan region, 60%-70% of inhabitants feel comfortable in traditional houses as compared to 20% inhabitants in modern houses [12]. Traditional dwellings can provide insights into reducing energy consumption and improving, thermal comfort [13]. Integrating traditional design strategies and material characteristics such as building contours, spatial proportions, windows, wall materials and thicknesses, and roof designs into modern building practices can improve climate resilience [14-16]. For example, the new village of Gurna designed by Hassan Fathi copes with the hot and dry climate through courtyards, orientation, location of openings, thick walls, and wind-blocking windows. Alatawneh and Germanà [17] demonstrated the feasibility of using indigenous building materials. The vernacular urban form of Bushehr, Iran shows its sustainability by utilising passive strategies rather than mechanical devices [4].

Several studies have confirmed the advantages of semi-open spaces in traditional dwellings for improving the indoor thermal environment in terms of space, materials, design strategies, and efficiency [18-20]. However, only a few studies were focused on human thermal comfort in such spaces. Rijal *et al.,* [21], who conducted a 40-day survey of the interior and semi-open spaces of traditional houses in five districts of Nepal during summer and winter, reported that the neutral temperature in semi-open spaces was higher than that in interior spaces. Ryu *et al.,* [22] investigated into human thermal comfort in a large medium of semi-open space between the front and back yards of a traditional house in Korea and they found that it was cooler in summer due to good ventilation. Yusoff *et al.,* [23] investigated into how access corridors affect the air flow inside an atrium in buildings under the hot and humid climate in Malaysia and the results of the study suggested that the presence of more airflow paths, such as access corridors connecting the atrium to the outdoors will be able to increase the airflow rate inside an atrium. Jin [24] showed that summer cooling energy consumption was positively correlated with the use of air conditioning and negatively correlated with the area of semi-open space. Most studies on semi-open spaces in traditional dwellings had focused on patios [25-27]. However, the patio is only a part of traditional dwellings to guide natural ventilation. The interrelation between various types of semi-open spaces in guiding natural ventilation should be considered comprehensively.

Therefore, traditional dwellings in the Tai Lake area were used as a case study to evaluate the ventilation performance and thermal comfort of the interior and semi-open spaces of the dwellings by field measurements of air temperature (T_a), relative humidity (RH), global temperature (T_g) and air velocity (V_a). In this way, the role of semi-open spaces in thermal environment regulation and potential application in modern dwelling design to reduce thermal discomfort were clarified.

2. Overview of Traditional Dwelling in Tai Lake Area

2.1 Climate Data in Tai Lake Area

In Tai Lake area, summer is hot, oppressive, wet, and mostly cloudy while winter is cold and partly cloudy. Temperatures usually range from 0°C to 33°C throughout the year. The minimum average temperature in winter is above 0°C, and the average temperature in summer is above 28°C. The average relative humidity throughout the year is above 60% and average relative humidity in June and July in summer is above 80%, which is a typical hot and humid climate (Figure 1). Min [28] pointed that natural ventilation was most effective during the hot and humid summer months when passive strategies were used to cope with this type of climate. The comfort time ratio in the Tai Lake area was 8.8% (32 days), mainly in May, September and October. However, inducing natural ventilation during the hot and humid summer months increased the comfort time ratio by 22.7% from June to September (especially June and September). If the thermal storage performance of the building was combined with a night ventilation strategy, the comfort time ratio could be increased by 14.8%.

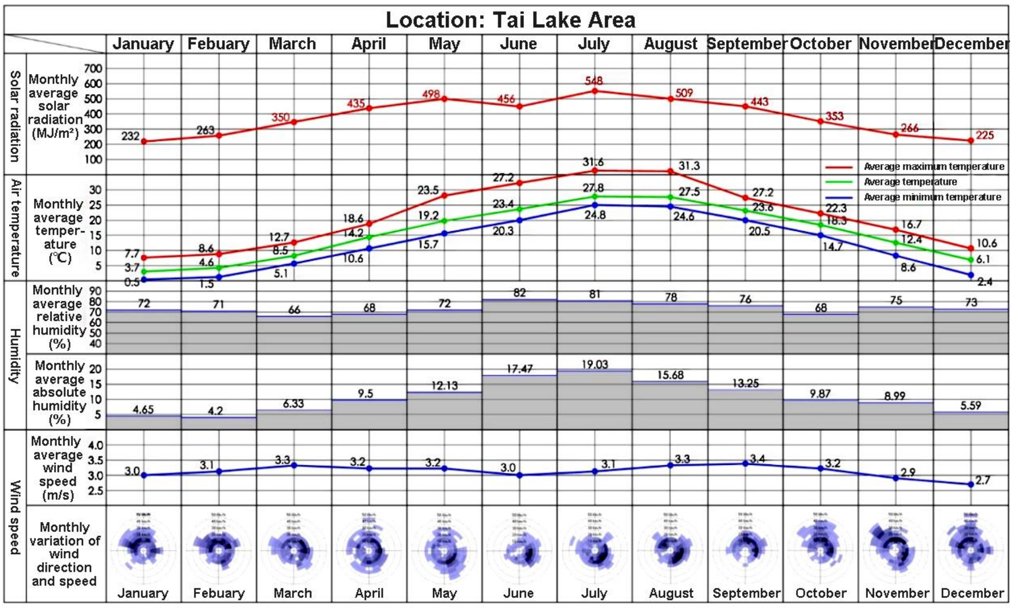


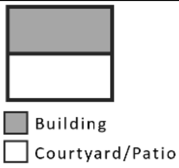
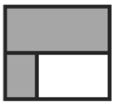
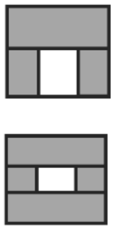
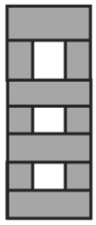
Fig. 1. Climate data in Tai Lake area in China [28]

2.2 Traditional Dwelling in Tai Lake Area

Considering that the natural ventilation of residential houses is not only related to the plan of the house, but also to the form of courtyard, dwellings in the Tai Lake area are classified into five types in accordance to three factors: plan of the building, relation between semi-open space and indoor space, and way of ventilation (Table 1) [29].

There are three main types of traditional dwellings: bamboo house, courtyard house and multi-courtyard house. Bamboo houses are commonly found in densely arranged villages and towns along the street or river. Because they cannot occupy too wide a street or river frontage. The width of courtyard is usually only one or two rooms, so the rooms are arranged vertically from front to back. Courtyard house has three sides of courtyard and four sides of courtyard as detached houses. The main room in the middle of the first floor is usually used as a living room, while the left and right rooms and side rooms are often used as bedrooms or other functions, while the second floor is usually used as bedrooms. Multi-courtyard housing is a combination of the above types of housing as the basic unit to form a larger courtyard, usually with inside alleys which connect the front and rear courtyards vertically. Modern dwellings, which are mainly Line-shaped houses and "L"-shape houses, are the result of people's pursuit of larger areas and more spacious courtyards, while ignoring the positive effects of semi-open spaces on climate regulation.

Table 1
The type dwelling in Tai Lake area

	Line-shaped house	“L”-shape house	Bamboo house	Courtyard house	Multi-courtyard house
Building plan					
Type	Modern dwelling	Modern dwelling	Traditional dwelling	Modern/Traditional dwelling	Traditional dwelling
Semi-open space	Courtyard	Courtyard	Patio/Inside alley	Courtyard/Patio	Patio/Inside alley

In this study, the focus was mainly on the multi-courtyard house type. The reason was that multi-courtyard house is a good representation of local traditional dwellings and it is well preserved and includes more semi-open space types.

2.3 Semi-open Space of Traditional Dwelling Tai Lake Area

The semi-open spaces of traditional dwellings in Tai Lake area are mainly patio (courtyard), inside alley, outside alley, under-eave space and entrance space (Table 2). Patio and courtyard are the products of enclosed architectural form, and they have the greatest influence on the indoor environment of traditional dwellings in Tai Lake area. It is equivalent to the air-exchange of enclosed residential buildings, providing natural lighting and ventilation [30,31]. The inside alley is commonly found in multi-courtyard dwellings and is located on the side of building with a width of about 1.2m to 2m, which is a passageway connecting the front and back buildings and patios [28]. Outside alley is located outside the building and is a passageway inside the village or town. There are many kinds of under-eave spaces, some of which have a traffic function, some of which only have an indoor-outdoor transition function, while some can be used for shading and cooling in summer and can utilise solar radiation during winter. Entrance spaces are commonly found in traditional dwellings and their main functions are for defence and privacy. Since this paper only focused on natural ventilation and thermal comfort of individual building, the main semi-open spaces measured and analysed in the study were patios and inside alleys.

Table 2
Semi-open space of traditional dwelling Tai Lake area

	Patio/Courtyard	Alley (inside)	Alley (outside)	Under-eave space	Entrance space
Ecological function	Ventilation and cooling; increased south-facing heat gain; use of solar radiation; shading	Ventilation; cooling	Shade cooling, ventilation cooling	Shade cooling	Induced ventilation for cooling
Physical function	Defence, privacy, creation of ecological micro-environments, spaces for interaction and leisure	Privacy, visual transitions, enriching spatial levels	Visual transitions, spaces for interaction	Creation ecological micro-environments, transport space, changing spatial proportions	Defence, privacy
Traditional dwelling	/	/	/	/	/
Modern dwelling	/ (only courtyard)			/ (a few)	

3. Research Methodology

In this study, traditional dwellings in the Tai Lake area were investigated by using the research method of field measurement. Thermal environmental parameters of indoor and semi-open spaces of three traditional dwellings, including air temperature (Ta), relative humidity (RH), global temperature (Tg), and air temperature (Va), were collected to assess and analyse the natural ventilation performance and thermal comfort, as well as application of these design strategies in the design of modern dwellings. The field measurement data were evaluated according to GB/T 50785-2012 Standard for Evaluation of Indoor Thermal Environment in Civil Buildings and ASHRAE 55 standard [32,33]. The test period was from 27 June 2023 to 7 July 2023.

3.1 Case Study Traditional Dwellings

Field measurements were conducted in three traditional multi-courtyard dwellings located in Suzhou City, Jiangsu Province, China (Figure 2). The permission was obtained from homeowners to use the three test buildings for research purposes and place appropriate instruments in the field. The three dwellings were called Building A, Building B, and Building C. All three buildings had three patios, but they had different patio sizes. In addition, Building A and Building C had inside alley while Building B did not. However, Building A and Building C also had different ways of connecting their inside alley to the patios. These constitute the main spatial variables of the study.

The specific measurement points for each building are shown in Figure 2. According to the measurement requirements of ASHRAE [33], all instruments were placed at a height of 1.1 m at centre of the room or space [34]. However, since the instruments were protected from direct sunlight during measurements, their positions in semi-open spaces were shifted slightly, depending on the sun exposure. However, positions too close to walls or vents were avoided to minimise errors.

(a)

(b)

(c)

Fig. 2. Test buildings and their measurement points (a) Building A (b) Building B (c) Building C

3.2 Physical Field Measurement

Field measurements were taken in patio spaces, inside alleys and major indoor spaces for air temperature, relative humidity and air velocity. Measurement points are shown in Figure 2. Global temperature was only measured in some patio spaces; therefore, the global temperature was equal to the air temperature when the operating temperature in the study was calculated because there were no significant heat sources in the spaces [33]. Main references for selection and use of the measurement instruments were ISO 7726, ASHRAE 55 2023 and GB/T 50785 2012 (Table 3), which are the most commonly used international references for measurements and provided important guidance for this study [32,33,35].

Table 3
Measurement instrument standards

	ISO 7726 1998 [35]		ASHRAE 55 2023 [33]		GB/T 50785 2012 [32]	
	Range	Accuracy	Range	Accuracy	Range	Accuracy
Air temperature	10°C-40°C	Required: ±0.5°C Desirable: ± 0.2°C	10°C - 40°C	± 0.2°C	-10°C - 50°C	± 0.5°C
Relative humidity	0.5 kPa - 3.0 kPa	±0.15 kPa	25% - 95% rh	±5% rh	10% - 100% rh	±5% rh
Air velocity	0.05m/s - 1m/s	Required: ± (0.05+ 0.05Va) m/s Desirable: ± (0.02+0.07Va) m/s	0.05 - 2m /s	±0.05 m/s	0.05 - 3m /s	(0.05+0.05Va) m/s

The instruments used in this measurement were (Table 4):

a. Cos-03 temperature and humidity recorders were placed semi-open spaces and main indoor spaces, at the centre of patios, inside alley and main rooms in ground floor and first floor. The instruments were positioned at 1.1 m above ground in order to record the values of air temperature (T_a), relative humidity (RH) for each space. Data were automatically recorded at every hour and measurements were taken 24 h a day.
b. RS-HQ global temperature recorders were placed at the centre of patio. The instruments were positioned at 1.1 m above ground in order to record values of global temperature (T_g) for the spaces. Data were automatically recorded at every hour and measurements were taken 24 h a day.
c. PM6252 digital anemometers were used to measure air velocity (V_a) at the centre of the semi-open spaces and main indoor spaces. The instruments were positioned at 1.1 m above the ground. Data was recorded manually at every hour and measurements were taken every day from 8am to 5pm.
d. A laser distance meter was used to measure building dimensions for building modelling during simulation.

In semi-open spaces, shaded areas were measured to protect devices from direct sun radiation. Prior to field measurements, all instruments were calibrated again to avoid discrepancies and to correct reading deviations.

Table 4
Instrument description

	Type of instrument	Measurement parameters	Range	Accuracy
	Cos-03 temperature and humidity recorder (Hight precision)	·Air temperature ·Relative Humidity	Air temperature: -40°C to 80°C Relative humidity: 0 to 100%RH	Air temperature: ± 0.1°C Relative humidity: ± 1.5%RH
	Cos-03 temperature and humidity recorder	·Air temperature ·Relative Humidity	Air temperature: -40°C to 80°C Relative humidity: 0 to 100%RH	Air temperature: ± 0.2°C Relative humidity: ± 2%RH
	RS-HQ-USB global temperature recorder	·Global temperature	-40°C to 120°C	± 0.2°C

	PM6252 digital anemometer	·Air velocity	Air velocity: 0 to 30 m/s	Air velocity: ± 0.2m/s

The automatic recording instrument was set to record data at every 1 h. The selected measurement periods were from 27 June 2023 to 1 July 2023 for Building A and Building B, and from 2 July 2023 to 7 July 2023 for Building C. According to the China Meteorological Administration (CMA), based on a 5-year average monthly temperature data, July was considered the hottest period in Suzhou. It was important to ensure that the data collected during this period is representative of typical weather in the area. Extreme weather fluctuations or anomalies that may bias the data were avoided.

3.3 Data Analysis and Evaluation Criteria

Quantitative data obtained from measurements were calculated and evaluated by using Microsoft Excel tool. For qualitative data architectural features descriptive statistics were used. Tables and charts were used to present the data and provide explanations.

In this study, an adaptive model was used to evaluate the thermal comfort of a naturally ventilated building and average wind speed index for the evaluation of ventilation effect. For the thermal comfort evaluation, the operating temperature could be calculated according to the formulae proposed by ISO 7726:

$$Top = \frac{Ta\sqrt{10v}+\bar{T}r}{1+\sqrt{10v}} \tag{1}$$

Where v is air velocity, in metres per second; $\bar{T}$r is the mean radiation temperature, in degree Celsius. The adaptive models were referred to the ASHRAE 55 standard and GB/T 50785, respectively, where ASHRAE [33] proposed the Adaptive Comfort Standard (ACS) [32]:

$$T_{comf} = 0.31T_{a,out} + 17.8 \tag{2}$$

T_{comf} is the optimum comfort operative temperature in °C. $T_{a,out}$ is the is monthly mean outdoor air temperature (°C). The month of July was chosen for this study as it is one of the hottest months in Tai Lake area. The average of outdoor air temperature in the area for July was 27.8°C. Therefore, by applying Eq. (2), the optimum comfort temperature was 26.4°C.

Further, the 80% and 90% acceptability limits of operative temperature were calculated as follows:

80% acceptability limits (°C) = T_{comf}± 3.5
90% acceptability limits (°C) = T_{comf}± 2.5

90 % acceptability temperature range was 23.9°C - 28.9°C, and 80% acceptability temperature range was 22.9°C - 29.9°C.

In GB/T 50785, the evaluation of naturally ventilated buildings was divided into Grade Ⅰ, Grade Ⅱ and Grade Ⅲ corresponded to adaptive predicted mean vote APMV: -0.5 ≤ APMV ≤ 0.5; -1 ≤ APMV < -0.5 or 0.5 < APMV ≤ 1 and APMV < -1 or APMV > 1 [32]. Calculation formula and range are shown in Table 5.

Table 5
GB/T 50785-2012 Thermal Comfort Evaluation of Naturally Ventilated Buildings [32]

	Grade I	Grade II	Grade III
Evaluation indicators	Top I, b≤Top≤Top I, a Top I, a=0.77Trm+9.34 Top I, b=0.87Trm-0.31	Top II, b≤Top≤Top II, a Top II, a=0.73Trm+12.72 Top II, b=0.91Trm-3.69	Top<Top II, b or Top II, a<Top
Scope of application	18°C≤Top≤28°C	18°C≤Top II, a≤30°C 16°C≤Top II, b≤28°C 16°C≤Top≤30°C	18°C≤Top II, a≤30°C 16°C≤Top II, b≤28°C

where Trm is the average outdoor weekly temperature. Calculations based on standard climate data for July, the acceptability temperature range for Grade I was 23.9°C - 28°C, as the range for Grade II was 21.6°C - 30°C.

In addition, the natural ventilation performance was evaluated based on average wind speed index. According to the Beaufort Wind Level Scale, wind speeds in the range of 1.5m/s - 3.4 m/s are usually considered the most pleasant, such that they provide a cool sensation without causing discomfort. Whereas indoor wind speeds are generally low, according to Grondzik *et al.,* [36], wind speeds below 0.25 m/s have no effect on comfort; wind speeds between 0.25m/s and 1.52m/s can reduce comfort by 1.1°C - 3.9°C. Therefore, wind speed values of 0.25m/s - 3.4m/s were optimal in the research.

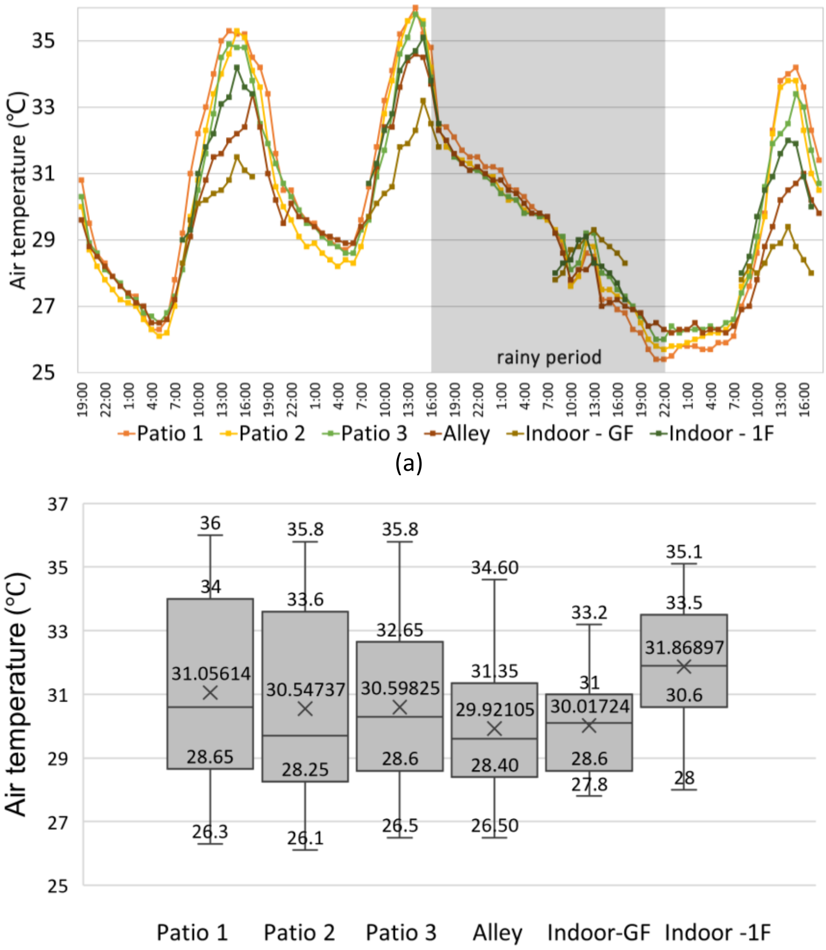
In conclusion, 21.6°C - 30°C was the acceptable operating temperature range for this study. And the average wind speed value of 0.25 m/s - 3.4m/s was considered to be the optimum value for natural ventilation assessment in the study.

4. Result and Discussion

4.1 Field Measurement and Data Analysis for Building A

Building A had a total of six measurement points, including three patios, one inside alley, and indoor spaces at the ground floor and first floor. Amongst them, the temperature and humidity of semi-open space measurement points were automatically recorded 24 h a day, while only the air temperature and relative humidity during daytime (8am-5pm) were recorded for the indoor space. For air velocity, measurements were taken only during the daytime for the semi-open space due to the low wind speed in the indoor space, which was generally below 0.1m/s and hardly felt by the human body. All data fluctuations during the measurement period could be observed in the line charts below. However, the air temperature and relative humidity data collected during rainy periods were excluded from the analysis for determining maximum, minimum, and average values. This was because the data collected on rainy days interfere with the overall data, and only sunny day data were included to obtain more reliable results.

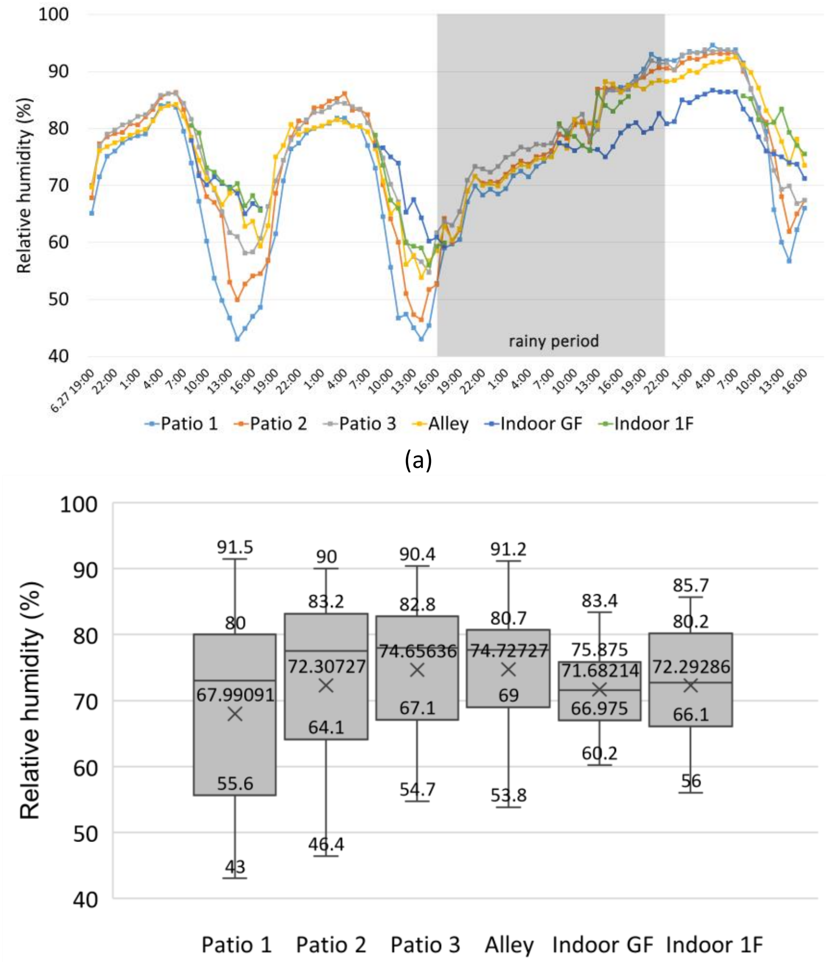
As can be seen from Figure 3, both indoor and semi-open spaces of traditional dwellings in Tai Lake area were hot in summer, but could be effectively cooled when rainfall occurred. The hottest daytime temperature in the semi-open space could be as high as 36°C, which was slightly higher than indoors. Indoor temperature of the ground floor was lower than that of first floor. By comparing the patios at different locations, it was found that the highest average temperature was 31.06°C in patio 1. The inside alley was cooler than all three patios, with the maximum temperature being more than 1°C lower than all three patios, which should be attributed to the fact that the inside alley was shaded. By comparing the inside alley in Building C, it could be observed that the temperature in the unshaded inside alley was not lower than that of patios in the same building. The temperature peaks in indoor spaces were always 1h - 2h later than in semi-open spaces, which suggested that temperature fluctuations in indoor spaces were influenced by the outdoor climate with a time lag. Overall, the air temperature in semi-open spaces was higher than indoor spaces during daytime and lower than indoor spaces during night. Patio 1 had the highest temperature while inside alley was the coolest of the semi-open spaces.



(b)

Fig. 3. Air temperature for Building A (a) line chart (b) box plot

In the Tai Lake area, summer rains were frequent, so humidity was high in both semi-open spaces and indoors (Figure 4). The general trend was that humidity decreases during the day with solar radiation and increases during the night, fluctuating between 43% and 94.6%. The fluctuations were much greater in semi-open spaces than in indoor spaces. Similarly, the average humidity in patio 1 was the lowest amongst the three patios at 67.99%, which was 4.32% lower than patio 2 and 6.67% lower than patio 3. The mean value of humidity in the inside alley was slightly higher than that in the three patios, especially when the sun's radiation was strong at midday. This is because the shaded alley absorbed less solar radiation, leading to higher humidity compared to the more exposed patios.



(a)

(b)

Fig. 4. Relative humidity for Building A (a) line chart (b) box plot

The wind speed magnitude was highly random. Therefore, in this measurement the method of averaging three consecutive measurements was used to reduce the error. As can be seen in Figure 5, the maximum average value of wind speed inside alley was 0.31m/s, which was much higher than that of patio. By comparing the three patios, it could be seen that the maximum average value of wind speed in patio 1 was 0.19m/s, while the minimum average value of wind speed in patio 3 was only 0.1m/s. This showed that the inside alley could effectively guide the ventilation due to its own size and spatial connection. Ventilation in the patio was also good, but the ventilation performance varied greatly from patio to patio, which might be related to size or the location of the patio.

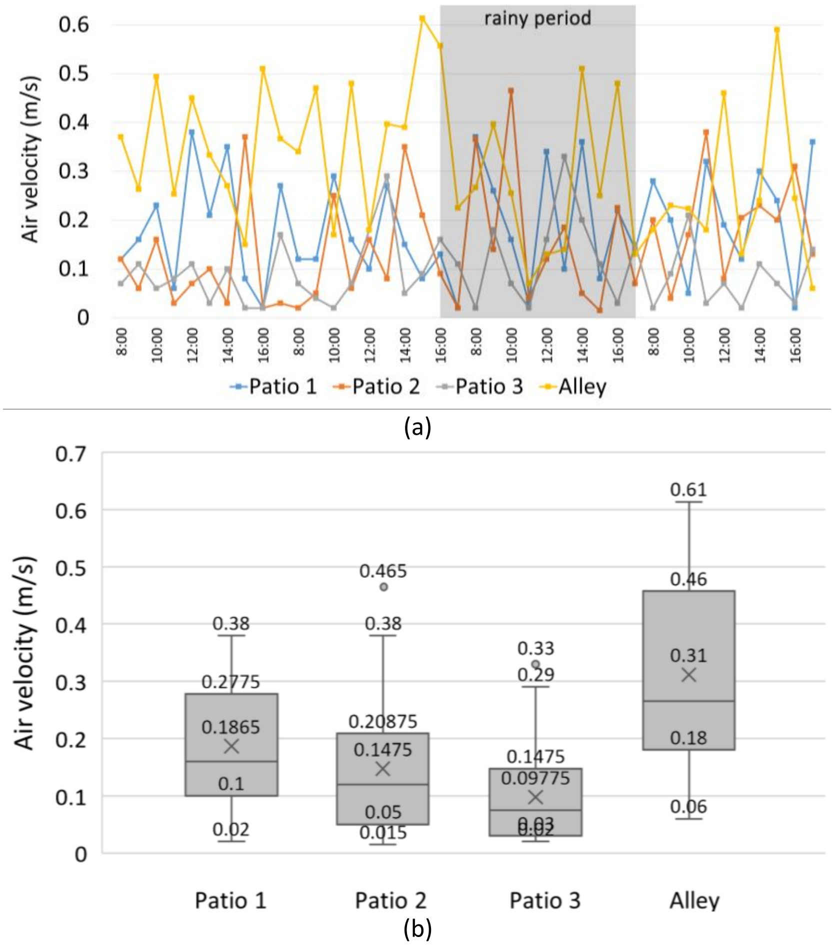


Fig. 5. Air velocity for Building A (a)line chart (b) box plot

In general, semi-open spaces were able to organise ventilation efficiently, but had higher daytime temperatures than indoor spaces due to solar radiation. The inside alley had the best ventilation and lowest temperature of semi-open spaces. Patio 1 had the highest temperature but the best ventilation amongst the three patios, probably due to its size and location.

4.2 Field Measurement and Data Analysis for Building B

Building B had a total of six measurement points, three patios and three interior spaces without inside alleys. All three indoor space measurements were taken on ground floor, as the building did not have a first floor. Air temperature and relative humidity measurements were taken only during daytime in all spaces. Measurements of air velocity was taken continuously only during daytime for semi-open spaces. Similar to Building A, air temperature and relative humidity data collected during rainy periods were excluded from the analysis for determining maximum, minimum, and average values. This was because the data collected on rainy days could interfere with the overall data. Therefore, only sunny days data were included to obtain more reliable results.

As shown in Figure 6, the air temperatures in the indoor and semi-open spaces of Building B fluctuated between 28°C and 36.9°C on sunny days, but a low temperature of 26.2°C could be monitored during rainy periods. The air temperature in the semi-open space was higher than that in indoor space, with a maximum difference of 2.37°C for mean value and 3.3°C for the maximum temperature. Different from building A, amongst the three patios, patio 3 had the highest temperature with a mean of 33.99°C and a maximum of 36.9°C. The lowest temperatures occurred during the rainy periods when the temperatures in all spaces were effectively reduced.

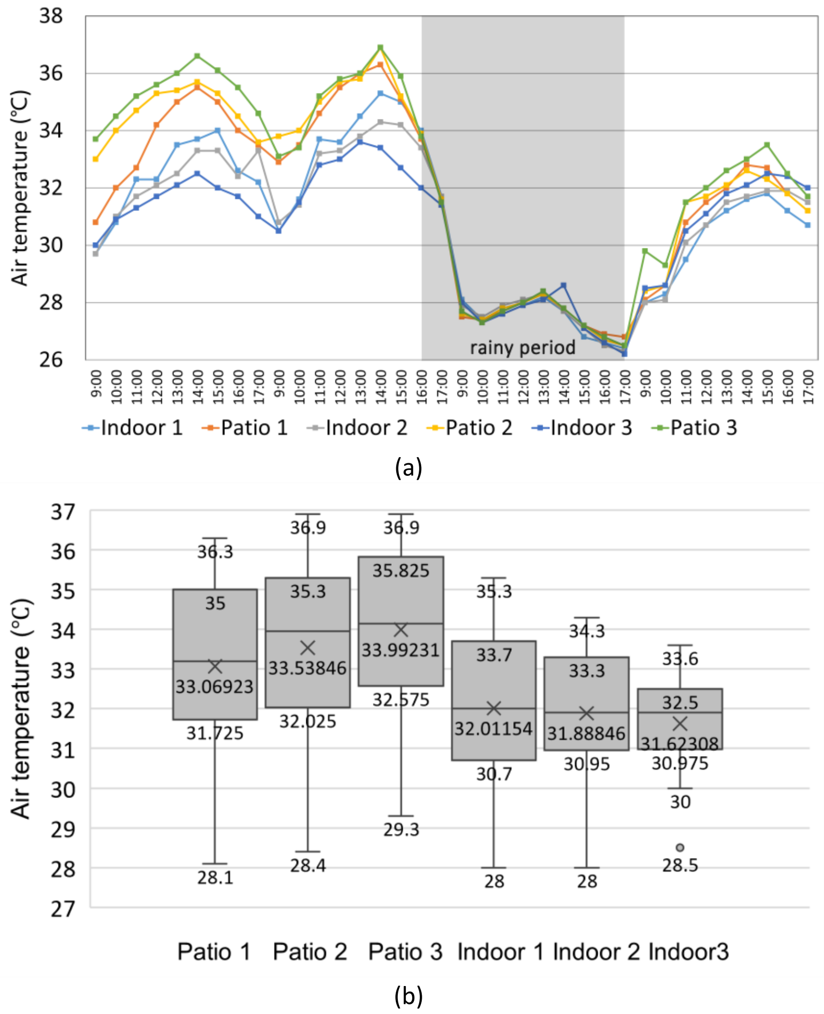
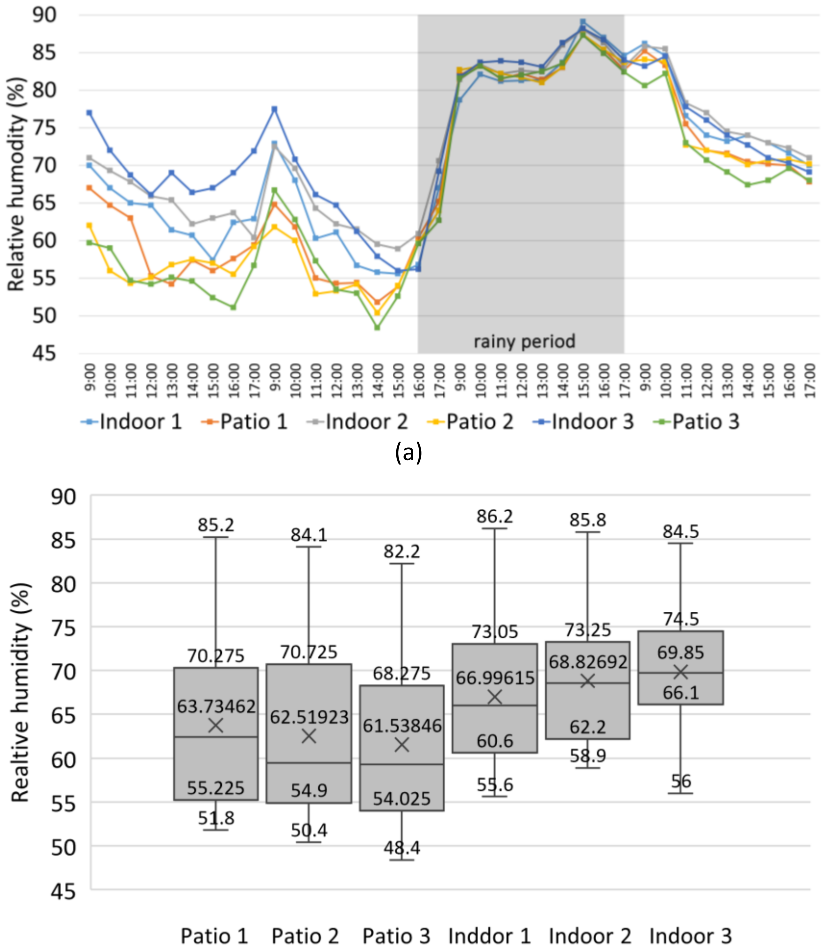


Fig. 6. Air temperature for Building B (a) line chart (b) box plot

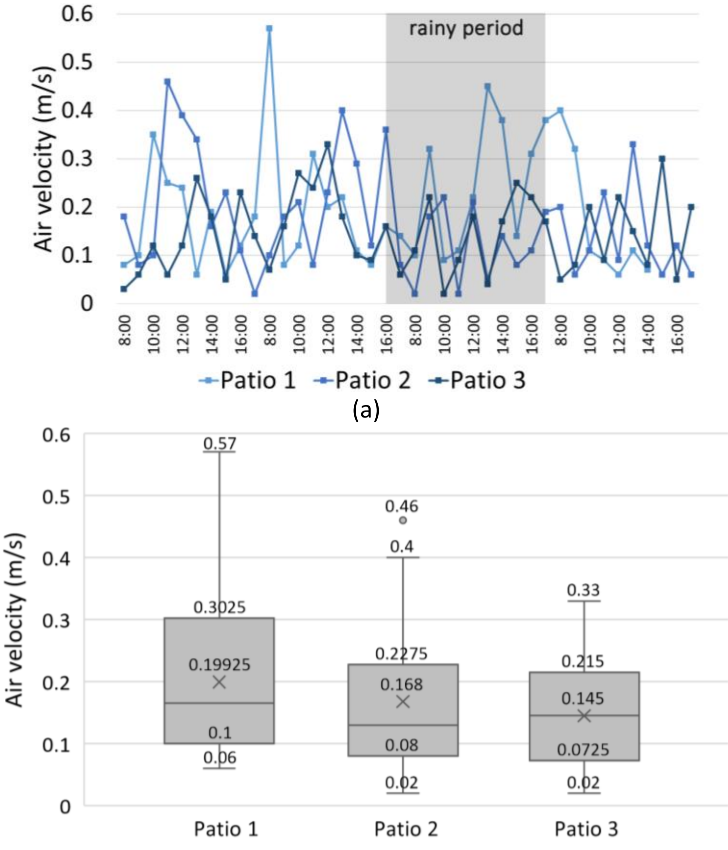
Figure 7 shows the pattern of change in humidity during daytime was the same as that of Building A. The average value of humidity in the patio was 61.54% - 63.73%, which was significantly lower than that in indoor space, which was 67% - 69.85%. The lowest values also differed significantly, with the lowest patio humidity value averaging 50.2% while that in indoor space was 56.83%. This significant difference was mainly due to the fact that Building B was measured only during daytime. Difference in the highest humidity values was small, averaging only 1.67 %, which was due to the fact that after rain the relative humidity rose significantly in both indoors and semi-open spaces. Meanwhile, the difference between different patios was not significant, Patio 1 was slightly higher than the remaining two patios by about 1%-2%. Finally, the lowest values of patio humidity usually occurred at 2pm, while the lowest values of indoor humidity usually occur at 3pm—4pm, indicating a lag not only in air temperature, but also in relative humidity.



(b)

Fig. 7. Relative humidity for Building B (a) line chart (b) box plot

Air velocity in the patio fluctuated between 0.02m/s and 0.57m/s. AS shown in Figure 8, comparison of air velocity values of the three patios revealed that the air velocity was the highest in Patio 1, the same patio as Building A, with a mean value of 0.2m/s and a maximum value of 0.57m/s. However, the fact was that the patios in Building A and Building B had different dimensions and proportions. In Building A, Patio 1 was 8.4m X 6.33m with a length to width ratio of about 1.33, while in Building B patio 1 was 10.95m X 5.3m with a length to width ratio of about 2.07. Therefore, both Patio 1 had the highest wind speed, which could be due to the orientation of building or distance from the gate. In addition, the air velocity data during rainy periods, Building A and Building B showed that the effect of rain on velocity was not significant.



(a)

(b)

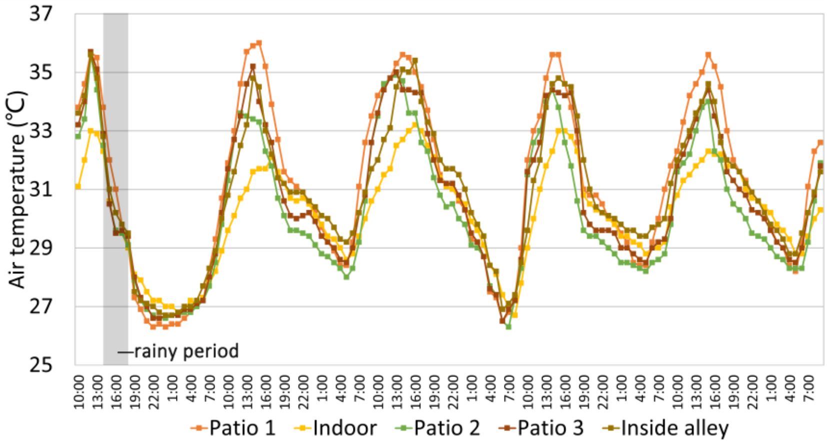
Fig. 8. Air velocity for Building B (a) line chart (b) box plot

Building B and Building A, measured at the same time and with the same building orientation, had many similar findings. Firstly, the temperature in semi-open space was higher than indoor space during the day due to solar radiation, while the relative humidity in the semi-open space was lower than the indoor space during the day. Secondly, the effect on temperature and humidity was higher during rain but not for air velocity. Finally, patio 1 in both buildings had the highest air velocity amongst the three patios.

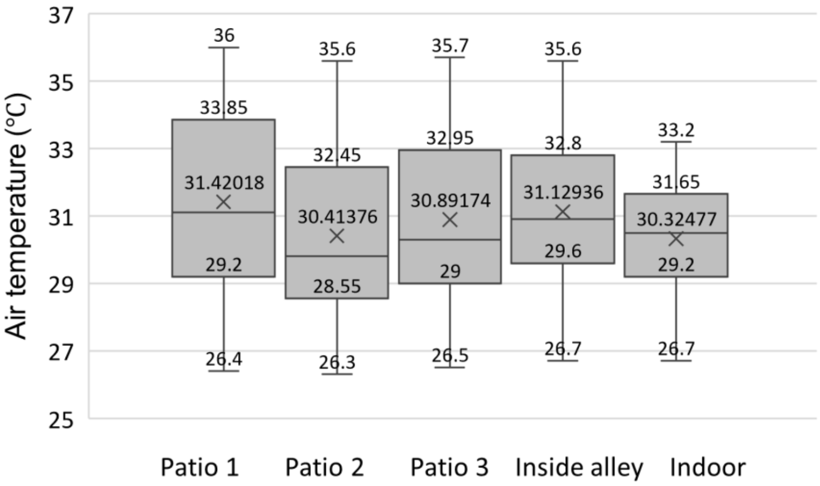
4.3 Field Measurement and Data Analysis for Building C

Building C had five measurement points, including three patios, an inside alley and an indoor space. The interior space measurement point was on ground floor, as the building was in a state of disrepair and the first floor was no longer open for safety reasons. Air temperature and relative humidity measurements were measured 24 h a day at all five measurement points. Air velocity was only measured during daytime (8am-5pm) at the 4 semi-open space measurement points. Consistent with Building A and Building B, air temperature and relative humidity data during rainy periods were excluded from the analysis to obtain more reliable results.

As shown in Figure 9, air temperatures in the indoor and semi-open spaces of Building C fluctuated between 26.3°C and 36°C during the measurement periods. The temperatures in the semi-open spaces were much higher than the indoor temperatures during daytime, with a temperature difference of more than 4°C at the widest gap. Amongst the semi-open spaces, patio 1 was the hottest at noon and space with the highest average temperature (31.4°C), which was due to the low building on the south side and less area with shade to receive more solar radiation at noon. So, the temperature of the space was not only related to factors such as size and material, but also had a great relation with building direction and the surrounding environment. At night there was not much difference in temperature between indoor space and semi-open space.



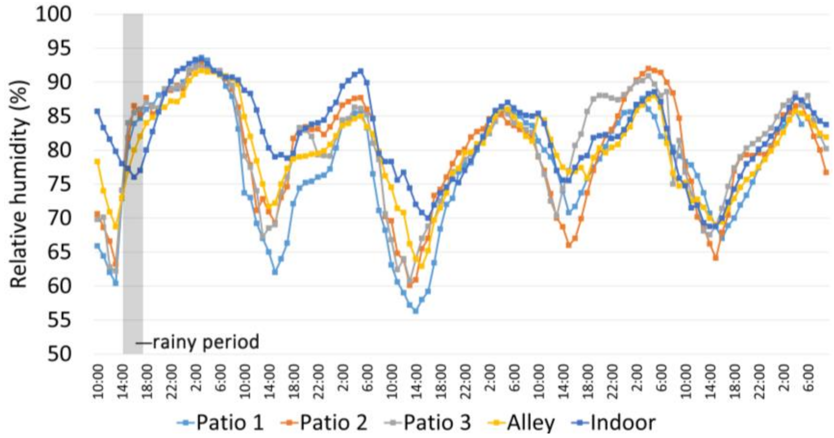
(a)



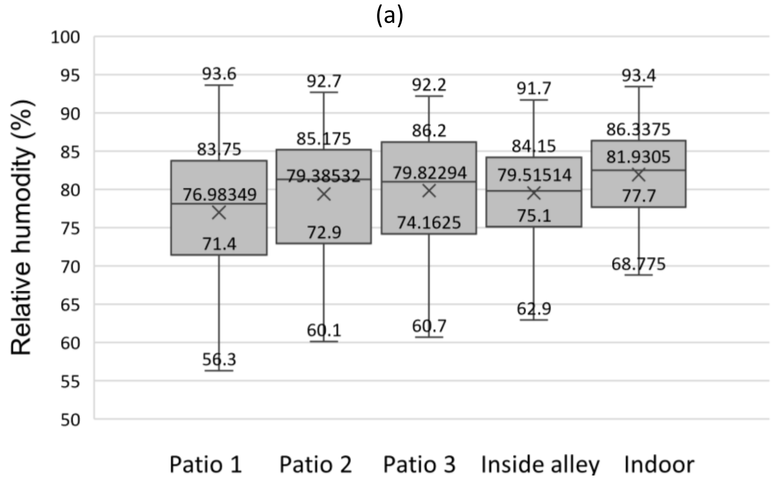
(b)

Fig. 9. Air temperature for Building C (a) line chart (b) box plot

As shown in Figure 10, the relative humidity in indoor spaces and semi-open spaces of Building C fluctuated between 56.3% and 93.6 during the measurement periods. The relative humidity at night was generally above 80%, while it was generally below 80% during daytime. And the indoor space was basically more humid than the semi-open space both during daytime and nighttime. And Tai Lake area was hot and humid in summer and the high humidity in indoor could be solved well by using natural ventilation. Amongst the semi-open spaces, patio 1 had the lowest mean relative humidity value of 77.98%, followed by patio 2 (79.38%), inside alley (79.52%), and patio 3 (79.82%).



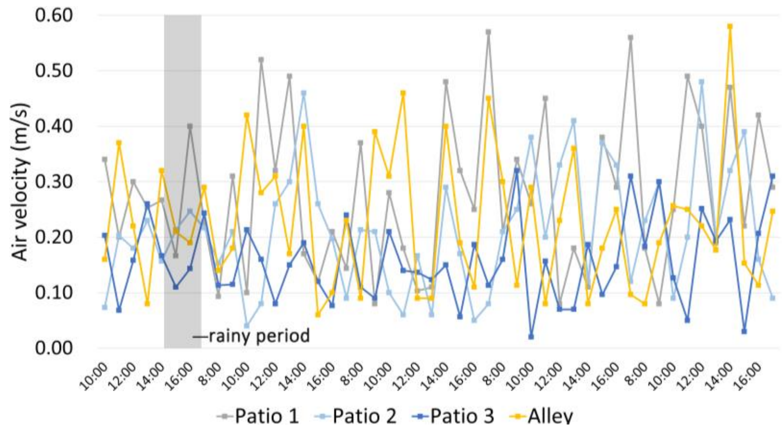
(a)



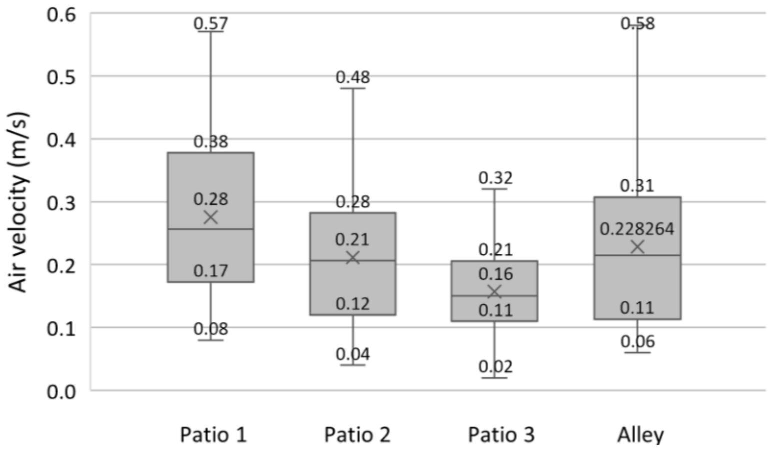
(b)

Fig. 10. Relative humidity for Building C (a) line chart (b) box plot

Ventilation performance in the semi-open space of Building C remained the best performing inside alley, with a mean value of 0.31 m/s and a maximum value of 0.61 m/s (Figure 11). The ventilation performance ranking of patios was strikingly similar to the two previously measured buildings, being patio 1 (mean 0.19 m/s) the best, followed by patio 2 (mean 0.15 m/s), and finally patio 3 (mean 0.1 m/s). The three buildings had completely different patio sizes and aspect ratios, but shared the same ventilation performance ranking. This might be related to the order in which the patios were arranged.



(a)



(b)

Fig. 11. Air velocity for Building C (a) line chart (b) box plot

Through environmental measurements and analysis of three multi-courtyard traditional dwellings with the same number of patios, it was found that the principle of passive cooling in semi-open spaces was to guide natural ventilation, and thus cooled the building, rather than the semi-open spaces themselves with lower temperatures, on the contrary, during the daytime semi-open spaces had much higher temperatures than indoor spaces due to solar radiation. Secondly, the relative humidity of indoor space was much higher than that of semi-open space. And in the hot and humid environment of summer climate in Tai Lake area, it was especially necessary to guide the natural ventilation not only to reduce the temperature, but also to reduce the humidity and improve the thermal comfort. Finally, for the ventilation performance of semi-open space, inside alley was the best. And Patio 1, which was the first patio after entering, always had the best ventilation performance amongst the three patios.

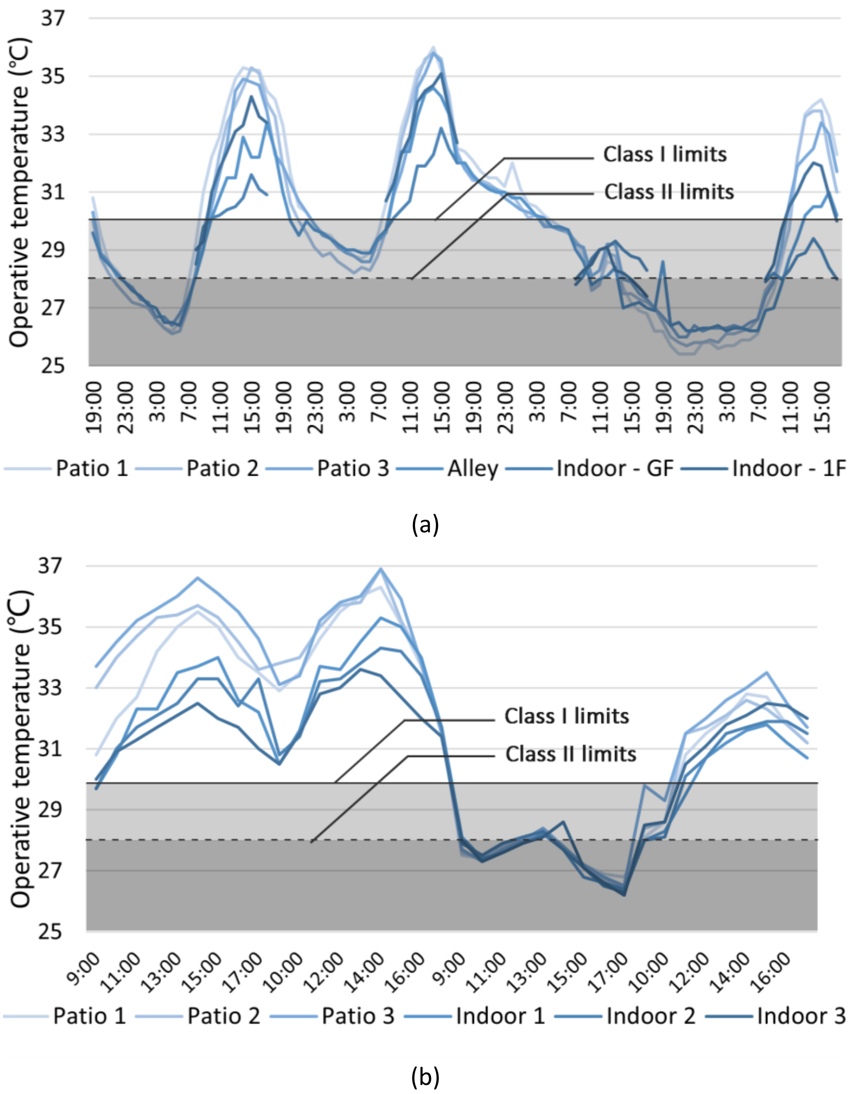
4.4 Discussions and Comparison to Thermal Comfort Standard

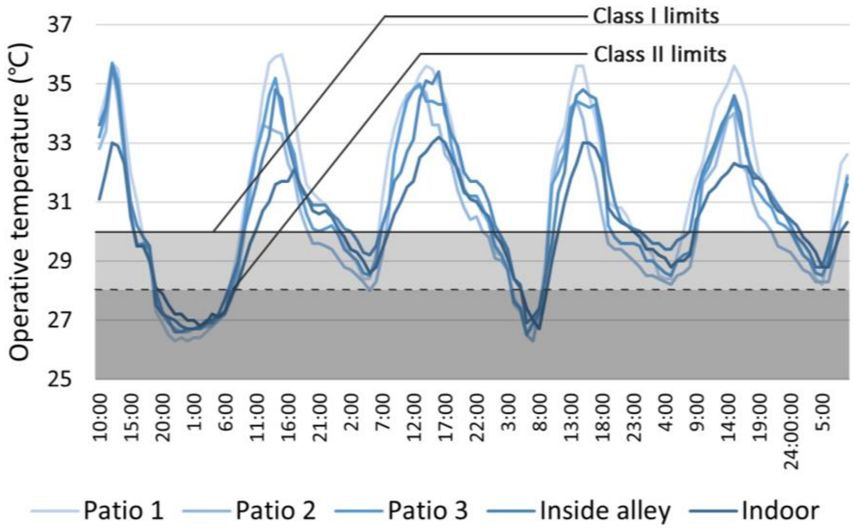
The evaluation criteria for natural ventilation and thermal comfort in this study were analysed and clarified in subsection 3.3. By referring to ASHRAE 55 Standard and GB/T 50785, 23.9°C - 28°C was Class I comfort temperature and 21.6°C - 30°C was Class II comfort temperature [32]. Based on this, the operating temperatures of the three buildings measured in the study and their compliance with the standards are shown in Figure 12. In addition, an average air velocity of 0.25m/s - 3.4 m/s was considered optimal for natural ventilation. The calculated percentage of time within measured data that met the criteria was summarised in Figure 13. It was worth to mention that air temperatures during rains were not counted in the analysis to ensure the accuracy and reliability of the data.

As shown in Figure 12 and Figure 13(a), Building A performed better in terms of thermal comfort during the all-day time period, with the semi-open space that meet the Class I criteria an average of 19.74% of the time and the Class II criteria 52.52% of the time. Semi-open spaces of Building C met the Class I thermal comfort criteria only 9.87% of the time on average and Class II 38.83% of the time. Given that the difference in mean outdoor temperature between the two buildings during the measurement period was only 0.77°C, it was possible that the difference in thermal comfort between the two buildings was attributable to the small percentage of outdoor climatic factors, and possibly to the fact that Building A had more shading means, and thus the semi-open spaces received less solar radiation. This showed that passive strategic shading was also a very effective means of cooling in summer. Building A also had better performance during daytime, with indoor spaces that meet the

Class I thermal comfort criteria on average 5.18% of the time and Class II thermal comfort criteria 30.04% of the time. The indoor spaces of Building B met the Class I and Class II thermal comfort criteria only 2.57 % and 12.82 % of the time, respectively. Overall, the three buildings met the Class I thermal comfort standard only at night (after sunset and before sunrise). During the hottest time of the day (12pm-2pm), it was difficult to meet the thermal comfort criteria for either indoor or semi-open spaces. The use of passive strategies such as natural ventilation in the hot summer in the Tai Lake area could only improve thermal comfort but cannot completely solve the problem of thermal discomfort.

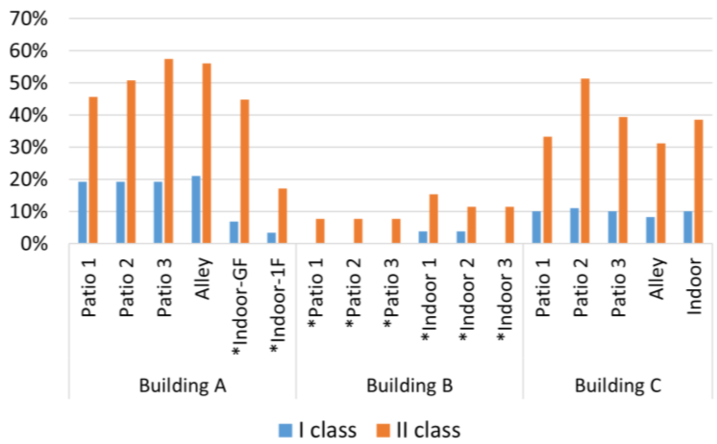
For natural ventilation performance (Figure 13(b)), the ventilation performance of the semi-open space of Building C was the best, exceeding the air velocity of 0.25 m/s 56.3%, 33.3%, and 12.5% of the time in patio 1, patio 2, and patio 3, respectively, while the air velocity of the patios of Building A and Building B exceeded the air velocity of 0.25 m/s only between 5% and 32.5% of the time. Secondly, the ventilation performance of the inside alley was better than that of patio. The air velocity in the inside alleys of Building A and Building C exceeded 0.25 m/s 62.5% and 41.7% of the time, respectively, which was 2-3 times higher than that of the patios (24.2% on average). Finally, the ventilation effect of all three building patios was better in patio 1 than in patio 2 than in patio 3. The exact reason may be further investigated by using numerical simulations.



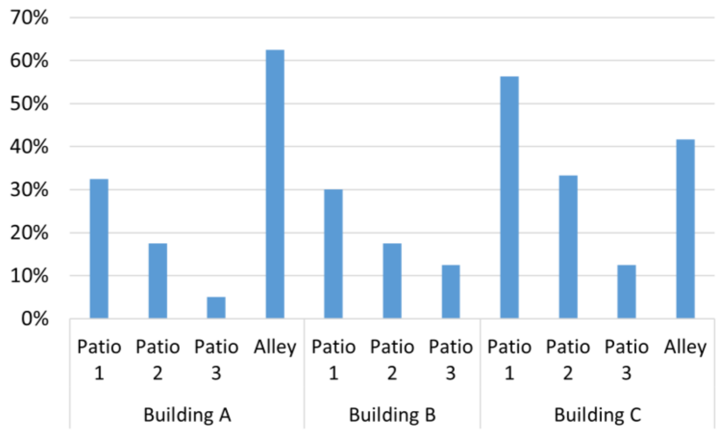


(c)

Fig. 12. Operative temperature (T_o) data and acceptable T_o range in (a) Building A (b) Building B (c) Building C



(a)



(b)

Fig. 13. (a) Percentage of time meeting Class I and II thermal comfort standards (b) Percentage of time with wind speeds above 0.25 m/s

5. Conclusion

Through field measurement and data analysis of the interior and semi-open spaces of three multi-courtyard traditional houses in the Tai Lake area. The conclusions were as follows:

i. The air temperature in the semi-open space was higher than in the indoor space, especially during daytime, when the maximum temperature difference could exceed 4 °C. The indoor temperature on the ground floor was lower than that on the first floor, which was related to building structure and exposure to solar radiation. The temperature peak in indoor spaces were always 1h - 2h later than semi-open spaces, indicating that the temperature fluctuation in indoor space was influenced by outdoor climate and has a lag. In addition, the temperature of roofed inside alley of Building A was significantly lower than that of its patios, especially at midday, while the average and maximum temperature of the open inside alley of Building C was similar to that of its patio system. In other words, the low temperatures in inside alley of Building A were probably due to shading measures.
ii. Relative humidity changes were the opposite of air temperature changes, with low humidity during the day and high humidity at night. The relative humidity of indoor space was much higher than that of semi-open space, and in the hot and humid summer climate of Tai Lake area, it was especially necessary to guide the natural ventilation not only to reduce temperature, but also to reduce humidity so as to improve the thermal comfort. The lowest values of humidity in semi-open spaces usually occurred at 2pm, while the lowest values of indoor humidity usually occurred at 3pm-4pm, indicating that, like temperature, indoor relative humidity changed with a lag.
iii. Semi-open spaces were effective in promoting ventilation. The inside alley had the best ventilation performance due to its own dimensions and how the space was connected. The patio 1, the one closest to the main door, was the best ventilated of the patios in all three buildings, probably due to its location and surroundings. The effect of natural ventilation on thermal comfort was not only to reduce air temperature, but also to reduce relative humidity, and thus reduce thermal discomfort.
iv. All three buildings met class II thermal comfort criteria only at night (after sunset and before sunrise). The time period for compliance with thermal comfort Class I was very limited and mostly during the rainy periods. During daytime, there was little time when both indoor and semi-open spaces met the thermal comfort criteria. Due to the high outdoor temperatures, by using only passive strategies such as natural ventilation can only improve thermal comfort to a certain extent, but it could not completely solve the problem of thermal discomfort. In addition, the ventilation performance of the inside alley was better than that of patio, with a longer period of time when the air velocity exceeded 0.25 m/s.

In general, semi-open spaces are effective in promoting natural ventilation to cool the building, while not having lower temperatures, on the contrary, semi-open spaces are hotter than indoor spaces, especially during daytime. The indoor thermal environment is influenced by the outdoor climate and has a lagging effect. In addition, the ventilation performance of inside alley is the best in semi-open space. The ventilation performance of patio is always better in patio 1 than in patio 2 than in patio 3. The reason for this may be related to the proportion of size of the patio, the location of patio or the external environment. Further research could use numerical simulation to identify the type, size and arrangement of semi-open spaces that affect ventilation and cooling, which is a direction for future research.

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