6 Spatial configuration, building micro-climate and thermal comfort

a modern house case[5]

ABSTRACT

In this paper, the authors attempt to clarify the relationship between spatial configuration, building microclimate and thermal comfort through the investigation of a modern house in hot and humid climate with spatial diversity. First, the spatial configuration of the house was analysed in detail. The spatial geometric features, spatial boundary conditions, and human activities in the building were categorised. Secondly, field measurements were conducted to investigate the microclimate of the house. The air temperature, relative humidity and wind velocity were monitored on typical summer days. Thirdly, a dynamic thermal simulation was performed to predict the thermal comfort performance of the building over the period of an entire summer. The simulated results were compared with the measurements, and the adaptive thermal comfort approach was used to evaluate the thermal comfort. The modern house studied was found to have a varied spatial configuration, similar to local vernacular buildings, which produces diverse thermal environments in

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the building. The microclimate of this specific building could provide considerable thermal comfort for the occupants in summer under the local climate conditions, although thermal comfort cannot be achieved through free-running model in the hottest days, mechanical cooling or mixed model are needed.

KEYWORDS Spatial configuration; Spatial diversity; Building microclimate; Summer thermal environment; Adaptive thermal comfort

6.1 Introduction

Space is a major aspect in contemporary architectural design that influences building functions and aesthetics as well as the physical and psychological sensations of a building's occupant. As the basic volume for human activities, the space of a building also constitutes the basic element of a living environment. A particular space can provide both a special environment and a microclimate significant to the occupants' living quality, which is determined by physical and psychological demands. This applies regardless of scale, whether at the regional, urban or neighbourhood level, or at the level of building block, building and room. At building scale, a building that has diverse spatial configurations can provide a rich and varied environment and can influence the way in which we use the rooms (movement, sequence and activities) and how we feel in them (related to temperature, light, sound and air velocity).

Spatial diversity in and around a building can therefore lead to variations in comfort over the various spaces. With free movement between the spaces, spatial and comfort diversity can lead to a better comfort for the inhabitants as they are able to choose the spatial environment that fits their activities and their comfort needs. A few studies were directed at spatial diversity and its environment (Andreou, 2013; Merghani, 2004; Niu et al., 2015; Spagnolo & de Dear, 2003; Steane, 2004; Steemers, Ramos, & Sinou, 2004; Tsiros & Hoffman, 2013). Du et al. (2014) studied the building microclimate at building scale for a Chinese vernacular house. The building microclimate was defined as the type of micro-climate that involves the indoor space as well as the spaces surrounding the indoor space (i.e. semi-outdoor space and outdoor space). The paper showed that the building microclimate of the vernacular building was different for different spaces. This vernacular building, therefore, was able to offer a different comfort in different spaces leading to an increased comfort over the entire day by moving from space to space over the day.

However, the house then studied was large and built in a traditional architectural spatial style. Sadly, modern residential buildings are currently losing their spatial diversity (Du, Bokel, & Dobbelsteen, 2016). There are a number of reasons for this, namely: 1) the number of people living in the city has risen, limiting the living area per household; 2) the wide application of mechanical ventilation, heating and cooling; and 3) the occupants' higher demands with regards to comfort 4) the high building construction speed and the low building cost of the modern houses.

This loss of spatial diversity is causing a poorer quality of the building microclimate; especially with regards to thermal comfort. Not only is the thermal comfort of the occupants becoming increasingly difficult to achieve in a free-running (non-air conditioned) modern house without spatial diversity, but the energy consumption of these buildings also continues to rise. In this study, the authors focus on the effects of building spatial design on the building microclimate, and then on the residents' thermal comfort. They want to answer the question if a good building microclimate be achieved in a modern house through an appropriate spatial configuration, providing thermal comfort through the use of an all passive system.

After a broad survey of modern houses in the hot and humid region of China, the authors found a modern house with a design offering a diversity of spaces. The studied house is situated in Chongqing located in the southwest of China. The selected object of this study is an untenanted house with no interior decoration, making it ideal for the purpose of this research, as the intrinsic thermal environment could be studied without any disturbances of the occupants.

The spatial configuration, the building microclimate and the thermal comfort of the house were studied. First, the spatial configuration of the house was analysed in detail. The spatial geometric features, spatial boundary conditions, and human activities in the spaces were categorised. Secondly, field measurements were conducted on typical summer days to investigate the building microclimate of the house. Air temperature, and relative humidity were monitored in the various spaces of the house. The air velocity was measured in detail at key points throughout the ground floor area. Thirdly, a dynamic thermal simulation was performed to determine the thermal comfort performance of the building over the period of an entire summer. The simulated results were compared with the measurements and the adaptive thermal comfort approach was used to evaluate thermal comfort. The relationship between the spatial configuration, the building microclimate and the thermal comfort was discussed in the end.

6.2 Theory

6.2.1 Spatial configuration

6.2.1.1 Outdoor, indoor and semi-outdoor spaces

When we talk about different kinds of spaces on the building scale, conventionally these are divided into indoor space, outdoor space and semi-outdoor space, reflecting their architectural functional design. Indoor space refers to space that is surrounded by walls, windows or doors and covered with ceilings, roofs or roof windows. It is the most common and important space for the occupants' daily life. It might be a closed space that is separated from the outdoor environment. The outdoor space is defined as the space included in the building, but lacking a ceiling, roof or roof window; hence a space that is directly exposed to the natural environment. Courtyards, patios and gardens are the main components of this category. In this context, a courtyard is identified as having a small height-to-width ratio and a patio is identified as having a large height-to-width radio. A garden is a big green space that is not completely surrounded by rooms. The semi-outdoor space, which is also known "grey" space or "buffer" space in architectural design, is a space featuring a semi-enclosed wall or roof. The semi-outdoor space is an important component in architectural spatial design. It can create various spaces and can connect the indoor spaces and outdoor spaces flexibly. The outside corridor, terrace, balcony and veranda are the main components used as transitional space. It should be noted that the three kinds of spaces can be transformed into each other through changing the spatial boundary conditions.

6.2.1.2 Spatial geometric features and spatial boundary conditions

Spatial geometric features convey the basic information about a space: size, height, area, horizontal location, vertical location and orientation. These parameters define the volume of the space and the relationship with the local environment: sun, earth, wind, and other buildings. Spatial boundary conditions refer to the floor, wall and roof which cover the space. Opening ratio (the ratio of the area that can be opened to relevant floor area), material use and adjacent conditions are the main boundary conditions. It should be noted that the definitions of indoor space, semi-outdoor space and outdoor space are determined by the opening ratio in the horizontal and vertical direction of the building space. If the horizontal opening is big enough, for example, if the roof is completely open, such as in the case of a courtyard or patio (the opening ratio is 1), the space is always considered an outdoor space. If the vertical opening is big enough, for example, one or two facades are completely open, the space is always considered a semi-outdoor space; examples are balconies, corridors, porches or vestibules. The opening conditions can be controlled in some spaces by opening or closing the windows or doors. An indoor space can thus be changed into a semi-outdoor space or an outdoor space. Such a space is known as an adaptive space.

6.2.1.3 Spatial design and adaptive comfort opportunities

As mentioned before, another function of spatial design is to provide different spaces that offer occupants opportunities to adapt their thermal comfort. The living style in this paper is separated into three different styles: daily life, sleep and study. According to adaptive thermal comfort theory, one kind of important adaptive behaviour is movement. If people are free to choose their location, it helps if there is plenty of thermal variety, giving them the opportunity to choose the places they like (Humphreys, 1997). Occupants can change their location for different activities. Movement is possible between buildings, between rooms, around rooms, out of the sun and into the breeze, and so on (Nicol et al., 2012). Buildings with diverse spaces provide opportunities for movement. Indoor space, semi-outdoor space and outdoor space are the three typical kinds of spaces. Atria, corridors, porches, patios and courtyards are commonly utilized elements to provide diversity in the types of space in the building. In hot and humid climates, occupants prefer to move from indoor spaces to semi-outdoor spaces. Occupants derive additional comfort from this adaption in two ways: physiologically, as more air movement can influence the comfort sensation, and psychologically, as people prefer an open environment in summer. Heidari (2000) spent a week studying how six subjects used different parts of their house in Llam (Iran) and concluded that the subjects tended to actively seek out the most thermally comfortable spaces in the house over the course of the day; also, Merghani (2004) conducted fieldwork in Khartoum, Sudan, where the climate is hot and dry. The results show that, if given the chance, people will make the best of the spatial diversity available.

6.2.2 The local climate

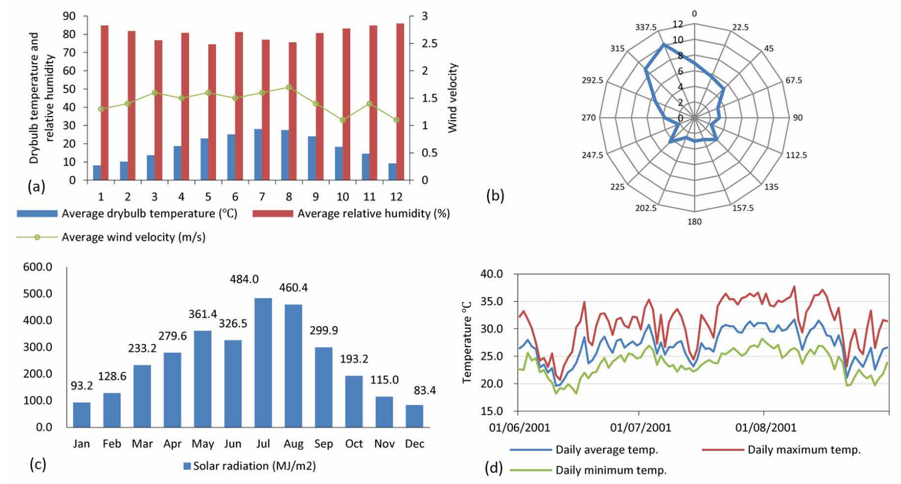

FIG. 6.1 Local climate features in the studied area. (a) Dry-bulb temperature, relative humidity and wind velocity (b) Wind rose (c) Monthly solar radiation (d) Dry-bulb temperature in summer

The studied house is situated in Chongqing, China. Chongqing is located in the southwest of China (longitude 105°11'–110°11' and latitude 28°10'–32°13') and belongs to the hot summer and cold winter zone according to the national "Standard of Climatic Regionalisation for Architecture". The hot summer and cold winter zone is the transient climate region between the cold and the hot zones of China, well-known for its hot and humid summer. Figure 6.1 (National Meteorological Information Center of China Meteorological Administration & Department of Building Technology Tsinghua University, 2005) (a) (b) (c) illustrates the weather features over an entire year. The annual average temperature is 16 to18°C, and the annual relative humidity is 70% to 80%; the extreme maximum temperature is 41.9°C and the extreme minimum temperature is -1.7°C. The levels of yearly solar radiation are high, especially in July and August with a maximum value approaching 500MJ/m^2, while the total solar radiation in July and August accounts for 31% of the yearly radiation. The yearly prevailing wind comes from the northwest and the average wind velocity is 1.6 m/s. Figure 6.1 (d) shows the temperature features in a typical summer. According to the weather data, the temperature is relatively mild from June to the middle of July. The temperature changes quickly and is unstable in this period. From the middle of July to the middle of August, the temperature remains at a stable high level. These 30 to 40 days are the hottest days in summer. After this period, the average temperature decreases, with some days that are nonetheless relatively warm.

6.2.3 Thermal comfort

The adaptive thermal comfort theory can be used to determine the comfort in a free-running building, since the relationship between indoor comfort temperature and outdoor monthly mean temperature for free-running buildings was found to be closely linear in Humphreys's field survey (Nicol & Humphreys, 2002). One of the main outcomes of the adaptive approach is the thermal comfort evaluation method based on field studies, in which the indoor thermal comfort temperature is shown to be a function of the outdoor temperature. The equation is: $T_n = A + BT_o$, where T_n is the neutral or comfort temperature (°C); T_o is the outdoor monthly mean air temperature (°C); and A, B are constants. The constants A and B are different in different climate regions and cultural contexts. They can be confirmed by field surveys in different regions. Some of the equations, especially applied to China for free-running buildings, are listed in table 6.1.

TABLE 6.1 Adaptive comfort equations (free-running model)

Location (source)	Equation
Humphreys (Humphreys & Nicol, 1998)	$T_n = 11.90+0.534T_o$
SHRAE Standard 55-2010 (ANSI/ASHRAE, 2017)	$T_n = 17.80+0.31T_{ref}$
EN15251-2007(EN15251, 2007)	$T_n = 18.80+0.33T_{rm}$
China (general) (Yang, 2003)	$T_n= 19.70+0.30T_o$
Shanghai, China (Ye et al., 2006)	$T_n = 15.12+0.42T_o$
Chongqing, China (Li, 2008)	$T_n = 16.28+0.39T_o$
Harbin, China (in summer) (Wang et al., 2010)	$T_n = 11.802+0.468T_o$

Here T_n is the neutral comfort temperature (°C); T_o is outdoor monthly mean temperature (°C); T_{ref} is the prevailing mean outdoor air temperature (°C) (for a time period between last 7 and 30 days before the day in question); T_{rm} is the exponentially weighted running mean of the daily outdoor temperature of the previous seven days.

Another important issue relating to adaptive comfort is the influence of humidity and wind velocity. In free-running or naturally ventilated buildings, the influence of humidity and wind velocity on the thermal comfort sensation of the occupants in hot and humid climate regions is greater than in other climate regions and in conditioned buildings. The cooling effect of air movement depends on not only air velocity but also temperature, humidity and radiation balance, as well as on the activity (metabolic rate) and clothing of the individual (Szokolay, 2000). Studies done in different climates show that occupants prefer greater air movement and that comfort ranges can expand with the aid of air movement (Mishra & Ramgopal, 2013). In hot and humid climate areas, air movement can promote convective heat transfer from the skin and increase the evaporation of sweat. Occupants appreciate air movement, even when it is not necessary for direct cooling (Zhang et al., 2007). In order to approximate the potential cooling effect of elevated air velocity and how this can compensate for a room's high operative temperature, some functions were proposed by ASHRAE Standard 55, EN15251 and functions by other researchers are listed in table 6.2.

TABLE 6.2 Effects of air movement on comfort temperature

Source	Comfort temperature Correction for enhanced air velocity	Conditions
ASHRAE Standard 55-2010 (ANSI/ASHRAE, 2017)	ΔT=1.2, 0.3m/s<V_a<0.6m/s ΔT=1.8, 0.6m/s<V_a<0.9m/s ΔT=2.2, 0.9m/s<V_a<1.2m/s	
EN15251-2007 (EN15251, 2007) Nicol (Nicol, 2004)	$\Delta T = 7 - \frac{50}{4 + 10V_a^{0.5}}$	0.1m/s<Va
Szokolay (Szokolay, 2000)	$\Delta T = 6V_e\text{-}1.6(V_e)^2, V_e = V\text{-}0.2\ \mathrm{m/s}$	V<2m/s
China (Su et al., 2009)	$\Delta T = -4(\varphi\text{-}70\%) + \frac{0.55\mathrm{V}}{0.15}, \mathrm{T} > 28℃$ $\Delta T = \frac{0.55V}{0.15}, \mathrm{T} < 28℃$	V<0.8m/s

Here ΔT is the raise in comfort temperature (°C); T is the indoor air temperature (°C); V_a is the air velocity (m/s); V is the air velocity at the body surface (m/s); ϕ is the relative humidity (if less than 70%,ϕ =70%)

6.2.4 Spatial configuration, building microclimate and thermal comfort

Spatial design is an important passive cooling strategy, see figure 6.2. It can cool down the microclimate in two important ways: via solar control and natural ventilation. Solar radiation is the main factor that increases the building cooling load in summer. It denotes the complete or partial, permanent or temporary exclusion of solar radiation from building surfaces or interior or surrounding spaces (Geetha & Velraj, 2012). Orientation and shading (self-shading) are the major methods for solar control related to building spatial configuration. Natural ventilation is achieved by infiltration and allowing air to flow in and out of a building by opening windows and doors (Santamouris & Asimakopoulos, 1996). Wind driven and stack driven natural ventilation are the main styles. Therefore, architectural spatial design has a significant effect on thermal environment, and especially on thermal comfort. The influence of the spatial configuration is two folds: in the first place, spatial design can influence the building microclimate directly. An appropriate spatial design can, for example, cool down the building microclimate in summer. In the second place, it can provide adaptive comfort opportunities for the occupants, which is significant for summer thermal comfort.

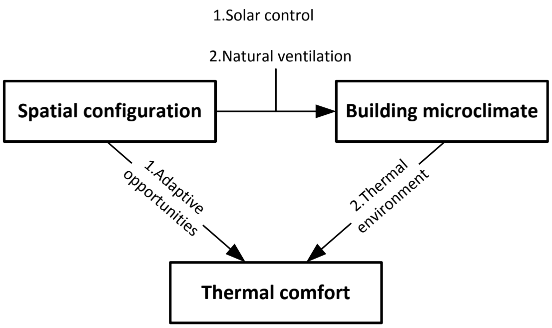

FIG. 6.2 The relationship between spatial configuration, building microclimate and thermal comfort

6.3 Method

6.3.1 Profile of the studied house

The selected house is a town house located in a suburban district of Chongqing constructed in 2010. The house is situated in a residential community with mixed building types. It is located on a cliff and faces 12 degrees off south-east (Figure 6.3). To the east of the house is a golf course with a huge green area. To the west of the house are three high-rise apartment blocks that are approximately 100 m high. The adjacent houses are built to the south and the north of the house. Figure 6.3 shows the location and overview of the environment of the house.

The total habitable floor area of the house is around 325 m^2. The house is around 8 m wide, with a depth of around 15 m. Figure 6.4 shows the plans, elevations and sections. There are four floors in the building. The basement floor (-1F) is a semi-basement with three of the walls underground because of the mountainous terrain. One of the walls on the ground floor (0F) is also under-ground, while the first floor (1F) and second floor (2F) are completely above ground. There are nine main rooms, three patios, two courtyards, one balcony and two terraces. A play-room and a garage are situated on the semi-basement. Patio 1 and patio 3 are on the semi-basement and the ground floor. The ground floor boasts a living room on the east-southeast side; a kitchen and dining room are located on the west-northwest side of the house. Patio 1, 2 and 3 were designed to surround the dining room. On the north-northwest side of the house is a courtyard with grass and trees. The first floor features two bedrooms facing east-southeast and a family room on the west-northwest part of the plan. Bedroom 1 has a balcony on the east-southeast; a grassy rear courtyard is located to the west-northwest of the house. On the second floor, the master bedroom and the study room are on the east-southeast side; one terrace faces towards at the west-northwest; another is near the study room.

FIG. 6.3 Location of the studied object and its environment

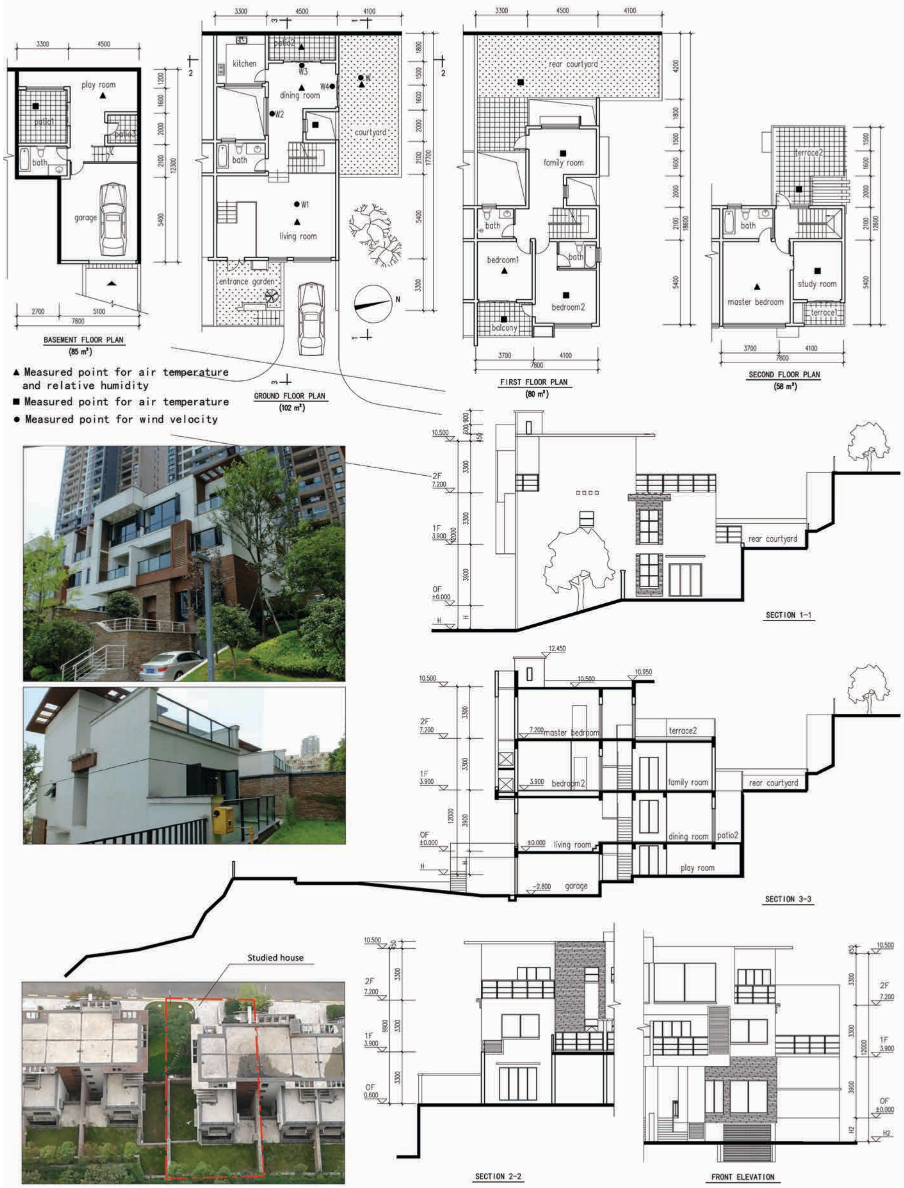

FIG. 6.4 Plans, elevation, sections, appearance and measurement points of the studied house in Chongqing, China

6.3.2 Building Microclimate Measurements

In this study, the authors focus on the affects of building spatial design to the building microclimate, and then for the residents' thermal comfort. There are some literatures about the physical environment measurements (Silva & Henriques, 2014; Wang, Long, & Deng, 2017) and simulation (Cardinale et al., 2013; Chen & Yang, 2015; Taleghani, Tenpierik, & van den Dobbelsteen, 2014b; Taleghani et al., 2013) for thermal comfort prediction. Therefore, the selected object of this study was an untenanted house with no interior decoration, making it ideal for the purpose of this research, as the intrinsic thermal environment could be studied without disturbance. For the investigation of the thermal environment, measurements were carried out in the house on typical summer days. The air temperature and relative humidity were measured in the various spaces of the house. The air velocity was measured in detail at key points throughout the ground floor space.

Building Microclimate measurements were performed in the summer period from August 18 to August 22 2014. The measurement points are shown in figure 6.4, and the measurement setup is shown in figure 6.5. Temperature and relative humidity were measured at 7 different points in the building, and the temperature was measured at an additional 8 points. The measurement instruments employed were automatic temperature loggers and temperature and humidity loggers recording data every ten minutes. The temperature measurement had an accuracy of 0.2°C; the humidity measurement had an accuracy of 5%. The instruments were located at a height of 1.2 m above the ground at the indoor and outdoor measuring points. The sensors measuring the air temperature and relative humidity at the outdoor points were protected by a white shield to minimise the radiation effect. Wind velocity was measured with the help of a manual anemometer with an accuracy of 5% of the value plus 0.05 m/s. During measurement periods, the house was free-running, in this case without occupants and mechanical ventilation. The house had no interior decoration and there were no doors in the interior rooms. The rooms could therefore be considered to be connected through holes in the wall. The windows and doors in the facades were semi-opened, which, because of the construction of the window, was the maximum open area. Before the measurements started on August 18, the weather was rainy. During the first three days of measurements (August 18-21), it was sunny and partly cloudy. On the last day, August 22, it was rainy again.

FIG. 6.5 The measurement setup in the studied house

6.3.3 Thermal comfort calculation

To evaluate the thermal comfort of the house, a dynamic thermal simulation was performed using DesignBuilder software, which is a comprehensive user interface for the EnergyPlus dynamic thermal simulation engine. Two simulations were performed. Firstly, the thermal environment of the house was simulated for the measured days (August 18-22) using actual outdoor weather data from the nearest weather station as the input weather data for the simulation. The simulated air temperatures in different spaces were compared with the measured data to validate the 3D model and simulation settings. Then, a dynamic thermal simulation of the house was performed during the entire summer (June 1 to August 31) using the typical meteorological year data from the EnergyPlus weather data for Chongqing to evaluate the summer thermal performance of the house.

Figure 6.6 shows the 3D model of the house in DesignBuilder. It should be noted that the patios were modelled as indoor spaces with roof windows because of the constraints of the software. This setting will influence the accuracy of the simulated thermal environment in the patios. However, the accuracy is assumed to be sufficient for the purpose of the present analysis, which aimed to compare the measurements with the simulations in order to be able to predict the temperature over a large time period and in all the rooms.

The characteristics of the simulated house and the characteristics of the building components are shown in table 6.3. The building performed as a free-running building with natural ventilation without any heating or cooling. In the case of validation, there was no activity setting that the house was operated without occupants and equipment corresponding to the actual situation. For the simulation of the entire summer, activity was set in terms of occupants and equipment were considered, and the internal heat loads were produced. The windows on the outside walls were assumed to be half opened and the roof windows in the patios completely opened, reflecting the actual situation. The infiltration was switched off, since infiltration heat that flows through the cracks is only a very small part of the summertime air flow, if the windows in the outside wall are half opened.

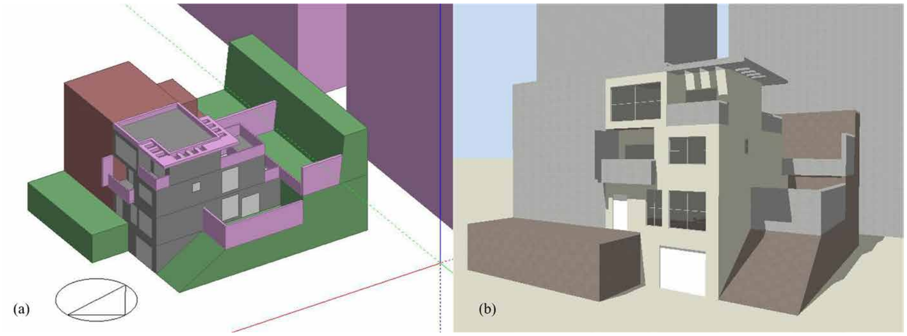

FIG. 6.6 Simulation model (a) 3D model (b) rendered model

TABLE 6.3 Input parameters of the simulation

Characteristics /component	Description		
Location	Chongqing		
Running model	Free-running		
Activity	Without occupants and equipment (for validation) With occupants and equipment (for entire summer)		
Natural ventilation	Natural ventilation-no heating/cooling, calculated, constant		
Construction	**Material**	**Thickness (mm)**	**U-Value (w/m²-k)**
External wall	Cement	5	0.86
	Insulation mortar	25	
	Aerated brick	200	
	Cement	20	
Internal wall	Cement	20	1.02
	Aerated brick	200	
	Cement	20	
Internal ground	Sand Stone	500	1.5
	Reinforced concrete	100	
	Concrete	40	
Internal floor	Cement	20	2.7
	Reinforced concrete	120	
	Concrete	20	
Roof	Concrete- lightweight	40	0.44
	Cement	25	
	Insulation Expanded polystyrene extruded	100	
	Asphalt felt	3	
	Cement	20	
	Concrete- lightweight	40	
	Reinforced concrete	120	
	Cement	20	
Glazing			
Outdoor window	DblLoE (e2=.1) Clr	6/9Air/6	1.78
Outdoor door	DblLoE (e2=.1) Clr	6/9Air/6	1.78
Roof window	DblLoE (e2=.1) Clr	6/9Air/6	1.78

6.3.4 Validation of the simulation with measurements

The hourly temperatures of the house during summer were obtained from the simulation. In figure 6.7, the simulated air temperature on the different floors was compared with the measured data obtained from the measured five days. The simulated results were found to fit well with the measured results: the simulated temperature variation showed the same trend as the measured results. The simulated temperature fluctuation was bigger than the measured one, indicating that the simulated minimum and maximum peak temperature were higher than the measured temperatures. Nonetheless, while a very small portion of the measured data fell within a 15% range of the simulated data, most fell within a 10% range of the simulated data. Therefore, the accuracy of the simulation was considered to be sufficient to obtain the thermal environment data of the house for the thermal performance evaluation.

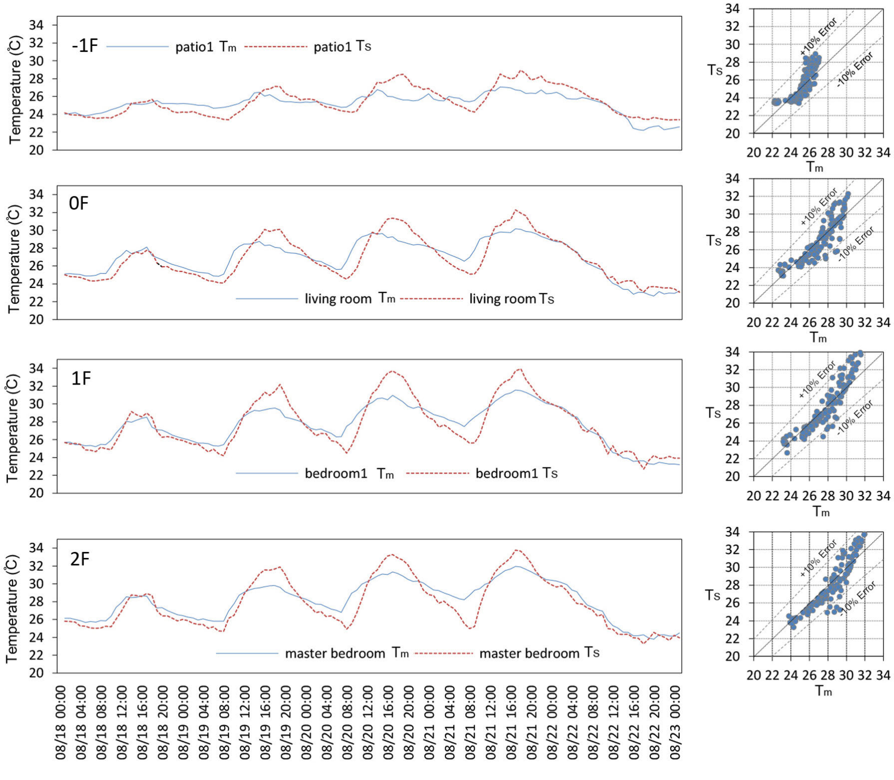

FIG. 6.7 Comparison of simulation results and measurement results.
Ts: simulated temperature, Tm: Measured temperature

6.4 Results

6.4.1 Spatial configuration

The different spaces in the house are characterised according to their spatial configuration. This spatial configuration consists of the spatial geometric features (height, size, horizontal and vertical location and orientation), the spatial boundary conditions (horizontal and vertical opening area, major materials and adjacent spaces), and the occupants' activities (daily life, sleep or study and the time periods that the spaces are used), as shown in table 6.4. The profile of the house shows that it was designed to create different types of spaces, not only in the horizontal but also in the vertical direction. Based on the spatial configuration the spaces were divided into indoor space, semi-outdoor space or outdoor space. The analysis of the different spaces in the building shows that a lot of different spatial configurations can be found in this building. The horizontal openings and the vertical openings have a large range, from 1.8 to 56 m^2 and 4 to 50 m^2 for the horizontal and vertical openings, respectively. The floor areas also differ a lot in size, from 4.2 m^2 to 42.1 m^2. The orientation of the vertical openings is only E-SE or W-NW, thus avoiding the South and South-West orientation.

6.4.2 Temperature measurements

Figure 8 illustrates the hourly air temperature and relative humidity curves in different rooms of the basement floor, ground floor, first floor and second floor over the entire measured period of five days. The average temperature measured rose from day one through day four, but decreased suddenly on the final day due to heavy rainfall. This short-term climatic shift is a characteristic weather feature of the local climate conditions: rainy weather can turn to sunny as the temperature rises, and back to rainy within a short period of time. Because of the rain, the last day was not included in the analysis. The trends of the curves were similar on the four days on which the measurements were taken, which means there was a similar variation in temperature over theses four days. During this period, the lowest reference outside temperature, T_{wst}, was around 24°C and the highest was 30- 35°C. The weather was relatively mild in this period, under the local summer weather conditions. The relative humidity followed the temperature trends, i.e. when the temperature increased, the humidity decreased. The humidity varied from 30% to 90%, which matches the highly humid summers of the local climate. Since the humidity followed the temperature trend, the further analysis focused on the temperatures; and because the temperature trends were similar over the four days on which the measurements were taken, the following analysis focused on one entire day, i.e., August 20.

Figure 6.9 shows the hourly average temperature curves and the temperature variations in different spaces on August 20, separated in indoor spaces (a) and outdoor space (b) and semi-outdoor spaces (c). The indoor temperatures were higher than the outdoor temperature in the period between 00:00-10:00 and 21:00 and 24:00. On the other hand, the indoor temperatures were lower than the reference outside T_{wst} in the period between 10:00-21:00. The trend of the indoor temperatures is very similar except for the playroom (in the basement) which has a constant 25°C. The difference in temperatures between the different spaces, except for the playroom, can be up to 2°C.

Comparing the outside temperatures, immediately noticeable is the sudden temperature change in the curves of patio2 and the rear courtyard. The temperature was found to soar swiftly to an extremely high level in a short period. The temperature in patio 2 rose suddenly at 12:00 from 30.5oC to peak at 38.8°C at 13:00, after which it quickly dropped to 32.2°C at 14:00. The reason is that patio2 is a very narrow space with a height-to-width ratio of 3; direct solar radiation was only able to reach the logger at the bottom of the patio during the period between 12:00-14:00. The temperature measured was influenced by the radiation, although radiation-shield instrument boxes were used to minimise this effect. Therefore, the actual curve (dashed curve) could be modified as the solid curve in this period based on the average increase rate before 12:00. Similar situations occurred at the measurement point in the rear courtyard. However, the rear courtyard was a relatively broader space than patio2, so the period during which it was heated up by direct solar radiation was longer on patio2. The curve of the rear courtyard was modified for the period between10:00-15:00. The measured temperature at the bottom of Patio1 remained very low and relatively stable, with a temperature fluctuation of only 2°C during the entire day. At night, all the measured temperatures in the outdoor spaces were almost at the same level as the reference outside T_{wst}. After the temperature increased at 7:00, patio1 peaked at 27°C (13:00), patio2 peaked at 32°C (corrected temperature) (14:00), patio3 peaked at 30°C (15:00), the courtyard peaked at 31.5°C (14:00) and the rear courtyard peaked at 35°C (corrected temperature) (13:00). As can be seen, the temperatures in the outdoor spaces were much lower than the weather station temperature (except for the rear courtyard), and there was a huge temperature variation in the outdoor spaces.

TABLE 6.4 Spatial design features in three aspects of the studied house

Space type	Space name	Spatial features in four aspects													
		1.Spatial geometric features						2.Spatial boundary conditions						3.Activities	
		Size (plan)(m)	Height (m)	Area (m²) S	Horizontal Location (from the centre of the house)	vertical Location (in floor)	Orientation (main windows)	Vertical opening area (m²) S_v	Vertical opening ratio S_v/S	Horizontal opening area (m²) S_h	Horizontal opening ratio S_h/S	Major materials 1. Roof or ground 2. wall	Adjacent spaces (major spaces)	Periods in use	Activities
1.Indoor space	Play room	4.5x2.8	2.2	12.6	-	-1	-	0	0	0	0	1.Concrete 2.cavity brick	Patio1,3	M,A, E,N	Daily life
	Living room	7.8x5.4	3.6	42.1	-	1	E-SE	2.2	0.05	0	0	1.Concrete 2.cavity brick	Dining room	M,A,E	Daily life
	Dining room	4.5x3.1	3.3	17.2	-	1	W-NW	22.3	1.30	0	0	1.Concrete 2.cavity brick	Patio 1,2,3, court-yard, living room	M,A,E	Daily life
	Bedroom 1	3.7x3.9	3.3	14.4	-	2	E-SE	2.2	0.15	0	0	1.Concrete 2.cavity brick	Bed-room2, balcony	N	Sleep
	Bedroom 2	4.1x3.6	3.3	14.8	-	2	E-SE	1.8	0.12	0	0	1.Concrete 2.cavity brick	Bed-room1, balcony	N	Sleep
	Family room	4.5x3.1	3.3	14	-	2	W-NW	2.5	0.18	0	0	1.Concrete 2.cavity brick	Pa-tio1,2,3, rear courtyard	M,A, E,N	Daily life
	Master bedroom	4.5x5.2	3.3	23.4	-	3	E-SE	3.0	0.13	0	0	1.Concrete 2.cavity brick	Study room, terrace1	N	Sleep
	Study room	3.3x3.9	3.3	13	-	3	E-SE	1.8	0.14	0	0	1.Concrete 2.cavity brick	Master bedroom, terrace1	M,A, E,N	Study

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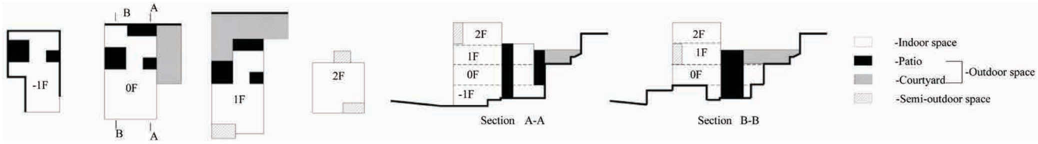
TABLE 6.4 Spatial design features in three aspects of the studied house

Space type	Space name	Spatial features in four aspects													
		1.Spatial geometric features						2.Spatial boundary conditions						3.Activities	
		Size (plan)(m)	Height (m)	Area (m²) S	Horizontal Location (from the centre of the house)	vertical Location (in floor)	Orientation (main windows)	Vertical opening area (m²) S_v	Vertical opening ratio S_v/S	Horizontal opening area (m²) S_h	Horizontal opening ratio S_h/S	Major materials 1. Roof or ground 2. wall	Adjacent spaces (major spaces)	Periods in use	Activities
2.Outdoor space	Patio 1	3.3x3.6	5.8	12	W-NW	-1, 1	-	-	-	12	1	1.Concrete 2.cavity brick	Play room, Dining room, rear courtyard	M,A,E	Daily life
	Patio 2	4.5x1.8	3.6	8.1	W-NW	1	-	-	-	8.1	1	1.Concrete 2.cavity brick	Dining room, rear courtyard	M,A,E	Daily life
	Patio 3	2.1x2.0	5.8	4.2	N-NW	-1, 1	-	-	-	4.2	1	1.Concrete 2.cavity brick	Play room, Dining room, courtyard	M,A,E	Daily life
	Courtyard	4.1x9.1	-	37.3	N-NW	1	-	-	-	37.3	1	1.Soil 2.cavity brick	Dining room, patio3	M,A,E	Daily life
	Rear courtyard	12x4.2	-	50	W-NW	2	-	-	-	50	1	1.Soil 2.cavity brick	Patio1.2, courtyard	M,E	Daily life
3.Semi-outdoor space	Terrace 1	3.3x1.5	-	5	E-NE	3	-	13.3	2.68	4	0.8	1.Concrete 2.cavity brick	Study room, Master bedroom	A,E	Daily life
	Terrace 2	4.7x3.1	-	14.6	W-NW	3	-	56.1	3.85	13	0.9	1.Concrete 2.cavity brick	Study room, Master bedroom	M,E	Daily life
	Balcony	3.7x2.1	3.3	7.8	W-NW	2	-	11.6	1.49	12	0	1.Concrete 2.cavity brick	Bed-room1,2	A,E	Daily life

TABLE 6.4 Spatial design features in three aspects of the studied house

The diverse space of the house in horizontal and vertical direction



The images of three kinds of spaces

1. Indoor space: 1(a) living room (b) dining room (c) bedroom1,2 (d) master bedroom	**2. Outdoor space**: 2(a)(e) patio1 (b) patio2 (d) patio3 (c) (g) courtyard (f) rear courtyard	**3. Semi-outdoor space**: 3(a) balcony (b) terrace2 (c) terrace3

**N-north; S-south; E-east; W-west; SE-south east; NW-north west*
**M-morning; A-afternoon; E- evening; N-night*

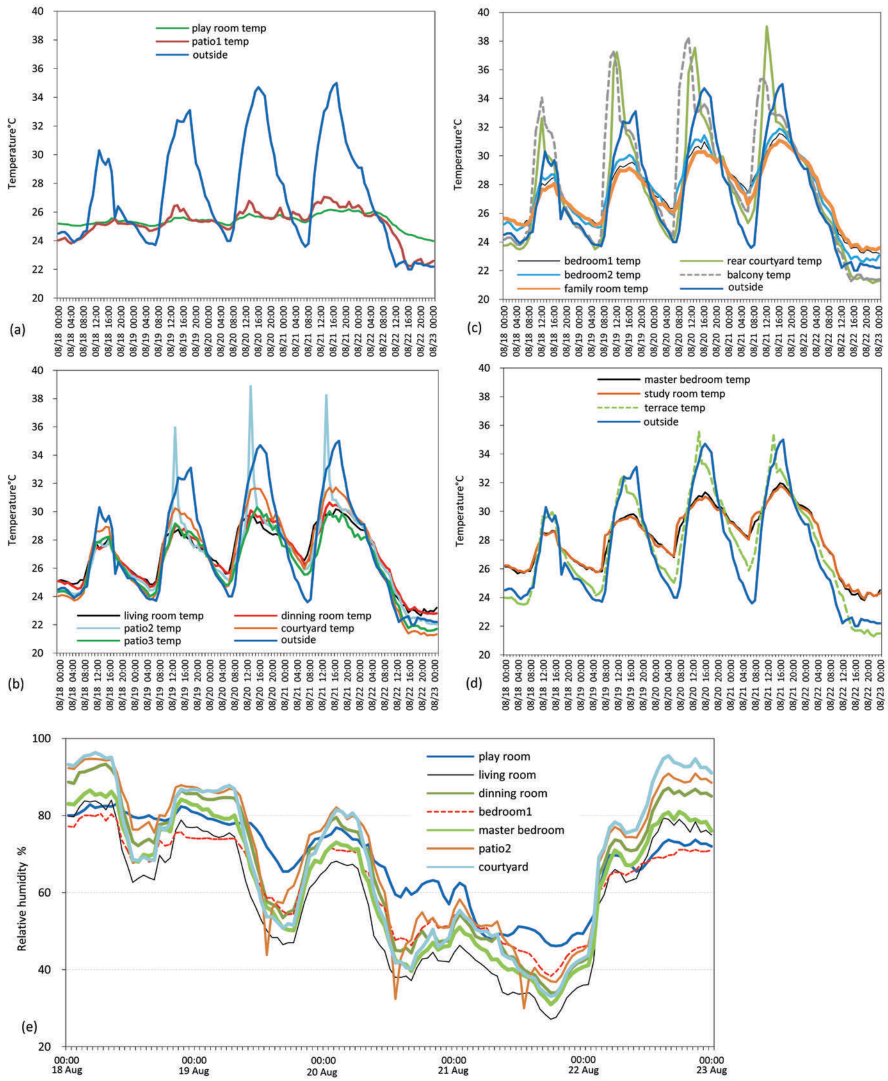


FIG. 6.8 Temperature and relative humidity curve of the measured points (hourly).
(a) temperature of the rooms in the basement floor (b) temperature of the rooms in the ground floor (c) temperature of the rooms in the first floor (d) temperature of the rooms in the second floor (e) relative humidity of the measured points

Figure 6.9(c) shows the temperatures in the semi-outdoor spaces compared with the reference outside T_{wst}. The semi-outdoor temperature curves were also modified during the period with direct solar radiation based on the same reason mentioned

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above. At night, the temperatures on the balcony and the terrace remained at the level of reference outside T_{wst}. The balcony temperature peaked at 34°C at 10:00 and the terrace temperature reached its peak at 33.5°C at 13:30 which is close to the weather station temperature.

Figure 6.9(d) shows the temperature variation in different spaces at different times. The temperatures in the play-room and patio1 were similar and much lower (4-7°C) than the temperatures in other spaces: outdoor, semi-outdoor or indoor spaces throughout the entire day. Except for these two spaces in the semi-basement, the night-time peak temperature in the indoor space was higher than the temperature in the outdoor and semi-outdoor spaces. This was reversed during the day, with the maximum difference of 4°C. The biggest difference in temperature variation was around 8°C in all of the compared spaces.

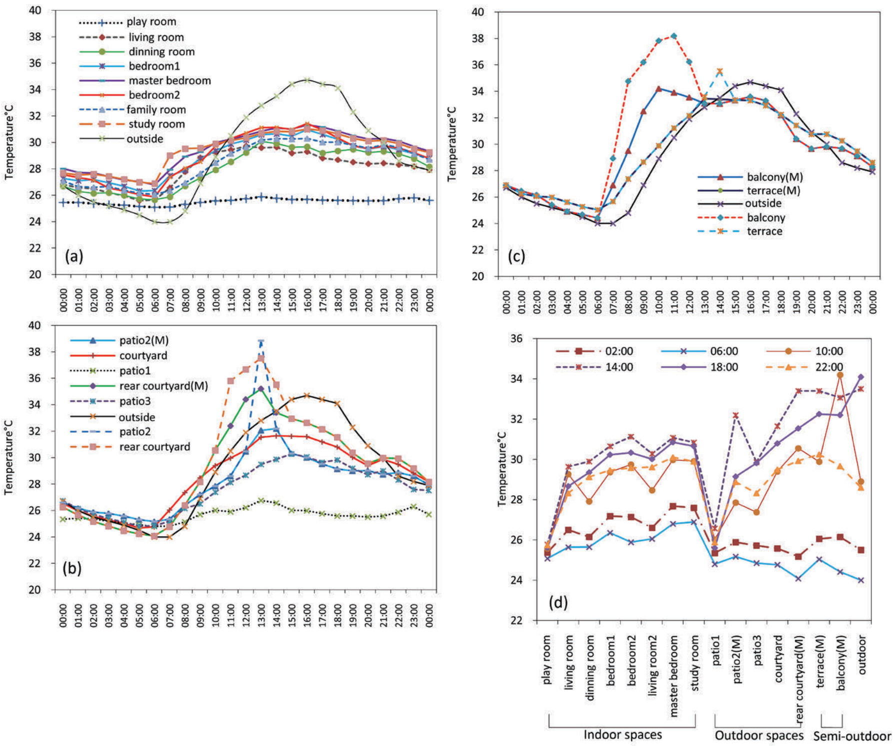

FIG. 6.9 Hourly temperature variation curve of the measured points on August 20 (M stands for modified) (a) Indoor spaces (b) Outdoor spaces (c) Semi-outdoor spaces (d) Temperatures in different spaces for different times over the day

6.4.3 Air velocity

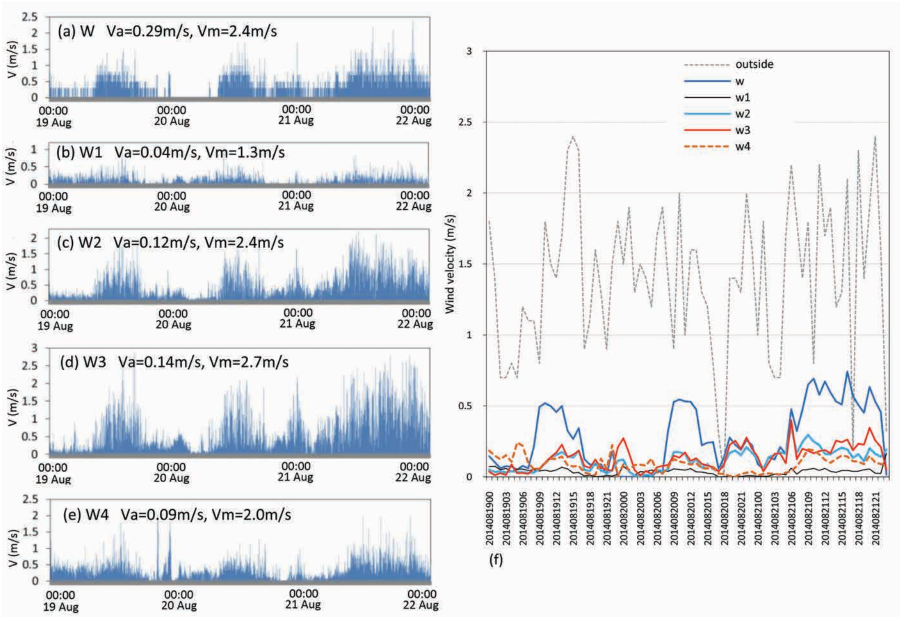

FIG. 6.10 (a)-(f) Wind velocity measured in different spaces
(a) Wind velocity in the courtyard (b) Wind velocity in the living room (c) Wind velocity near patio1 (d) Wind velocity near patio2 (e) Wind velocity near courtyard; Va: average wind velocity Vm: maximum wind velocity (f) Hourly wind velocity measured in different spaces and outside wind velocity at the weather station

Figure 6.10(a)-(e) shows the wind velocity per second in the period spanning August 19-21 at the measured points shown in figure 3. The wind velocity was found to follow the general trend of the observed temperature change for all of the measured points. The average wind velocity on August 21 was higher than on August 20, and higher on August 20 than on August 19. The results were matched with the temperature changes occurring over these three days. On one of the days, the wind velocity increased concurrently with the temperature and peaked at almost the same time as the temperature. The wind velocity was low at night. This indicated that the difference in temperature indoors and outdoors significantly influenced the air flow in this particular building environment. The graph also shows that the air flow was unstable and fluctuated from 0 to 2.7 m/s.

Comparing the average wind velocity (V_a) over these three days, it can be seen that the wind velocity in the courtyard (0.29 m/s) was higher than at a point near patio2 (0.14 m/s), followed by the point near patio1 (0.12 m/s), the point near the courtyard (0.09 m/s) and the point in the living room (0.04 m/s). Figure 6.10(f) shows the hourly average wind velocity at the measured points and the wind velocity recorded by the nearest weather station. The weather station wind velocity was much higher than the measured wind velocity in this specific building microclimate, owning to the location of the weather station in the open field, where it catches more wind. Another finding was that the outdoor wind velocity was irregular compared to the measured points in the building, which followed the temperature trends. Most of the time, the wind velocity in the courtyard was the highest in the building environment due to the fact that it is an outdoor space that easily catches the wind from all directions. The measured wind velocity at the points near patio1 and patio2 was higher than at the point in the living room, indicating both a low level of cross ventilation on the ground floor and that the stack ventilation in the patio contributed to the process of natural ventilation. In other words, the spatial diversity enhanced the natural ventilation. The results show that the wind velocity distribution is varied in the building.

6.4.4 Thermal comfort in summer

Figure 6.11 shows the simulated operative temperature of the house in the period of June-August and the comfort temperature zone. The comfort temperature zone is determined using the adaptive comfort approach for the Chongqing area as given in table 6.1 (Li, 2008). The relationship between the thermal comfort temperature and the monthly mean outdoor temperature then is: $T_n = 16.28+0.39T_o$, where T_n is the comfort temperature (°C) and T_o is the monthly mean outdoor temperature (°C); the range is 5.0-30.0°C (Li, 2008). According to this equation, the comfort temperatures in June, July and August are: 26.1°C, 27.2°C and 27.1°C. According to ASHRAE Standard 55, a comfort zone band of ±2.5°C corresponds with 90% acceptability, and ±3.5°C corresponds with 80% acceptability. So, the comfort zone, which in this case corresponds to 90% acceptability, ranges from 23.6-28.6°C in June, 24.7-29.7°C in July to 24.6-29.6°C in August.

On the relative mild days from June to the middle of July, the operative temperature was lower than the upper temperature limit of the comfort zone on most days. The building has the ability to provide a comfortable thermal environment for the occupants without mechanical cooling most of the time. During the hottest days, from mid-July to mid-August, almost all of the operative temperatures in the daytime exceeded the upper temperature limit of the comfort zone. Hence, a comfortable thermal environment could not be achieved in the building using the free-running model. On the relatively warm days at the end of August, the amount of time during which thermal comfort could not be achieved was limited, which means that the thermal environment of the building was acceptable most of the time. Table 6.5 shows the percentage of hours above the upper limit, in comfort range and below the lower limit in different spaces for the three periods mentioned above.

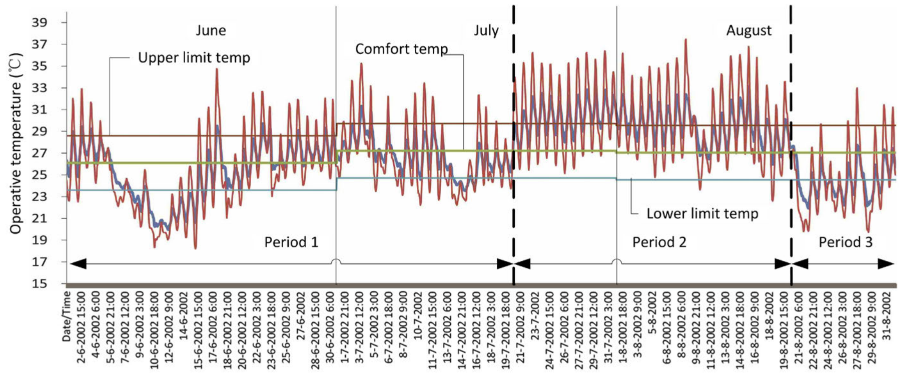

FIG. 6.11 Simulated operative temperature of the house during the entire summer (the red curve is the outside Dry-Bulb temperature and the blue curve is the operative temperature)

TABLE 6.5 Percentage of hours (24h per day) above the upper limit, in comfort rang, and below the lower limit in different spaces according to the different thermal periods (slightly warm, hot and warm) of figure 11

		Period 1(6/1-7/20) outside temperatures slightly warm			Period 2(7/21-8/20) outside temperatures hot			Period 3(8/21-8/31) outside temperatures warm		
		> (%)	=(%)	< (%)	>(%)	=(%)	<(%)	>(%)	=(%)	<(%)
B1	Patio 1	11.2	70.7	18.1	63.2	36.8	0	0	48.3	51.7
	Play room	2.8	77.6	19.6	47.4	52.6	0	0	43	57
GF	Living room	13.7	69.1	17.2	70.1	29.9	0	0.3	56	43.7
	Dining room	13.1	68.5	18.4	64.7	35.3	0	0.3	53.5	46.2
1F	Bedroom1	16.8	66.2	17	75.9	24.1	0	1.7	59.1	39.2
	Bedroom2	16.9	65.9	17.2	75.5	24.5	0	1.4	59.4	39.2
	Family room	15.6	67.4	17	71.2	28.8	0	1.4	59.1	39.5
2F	Master bedroom	20.6	64.3	15.1	79.8	20.2	0	2.4	66.4	31.2
	Study room	17.4	66.1	16.5	78.3	21.7	0	1	60.5	38.5

“>”-percentage hours above upper limit; “=”-percentage hours in comfort rang; “<”-percentage hours below lower limit

Figure 6.12(a) illustrates the total percentage of comfort hours, percentage of discomfort hours (temperature exceeded upper limit) and discomfort hours (temperature dropped below lower limit) in the different spaces for the entire summer. The percentage of comfort hours ranged from 49-65%, with the lowest percentage measured in the master bedroom and the highest in the play-room. It should be noted that the percentage of discomfort hours includes the hours when the operative temperature is below the lower limit. However, when the operative temperature drops below the lower limit of comfort temperature, in the studied area in summer, cold is relatively easy to solve, for example by wearing more clothes. If we disregard the discomfort hours when the temperature was lower than the lower limit of the comfort zone, the percentage of comfort hours stretches remarkable, see figure 6.12(b)). As we can see, the percentage of comfort hours varies considerably from one space to another. In the basement (play-room), the percentage that the temperature does not exceed the upper comfort limits was 83% and in the second floor (master bedroom), the percentage of hours that the upper comfort was not exceeded was only 62%.

Increased air movement can increase the number of comfort hours even more. According to the measured wind velocity in the living room and dining room, the average wind velocity was 0.04 m/s in the living room, which is too low to increase the comfort level. In the dining room, however, the average wind speed reached 0.14 m/s, which was high enough to influence the comfort temperature. Assuming the average wind velocity remains at 0.14 m/s in the dining room, according to Nicol's proposed equation, the comfort temperatures in June, July and August may be increased to 26.6, 27.8 and 27.6°C, respectively. The percentage of comfortable hours would then rise by 3% in June, 7% in July and 8% in August (figure 6.12(c)). Actually, the influence of the wind velocity in the dining room is even greater as the assumed wind velocity of 0.14 m/s represents the average over the three days on which the measurements were taken. The wind velocity was around 0.2 m/s during the daytime (9:00am-6:00pm), which is higher than it was at night. Calculated on the basis of the average wind velocity during the daytime, the percentage of comfortable hours would increase by 6% in June, 11.2% in July and 9.2% in August. Hence, during the daytime, the influence of wind velocity for comfort temperature is bigger than at night.

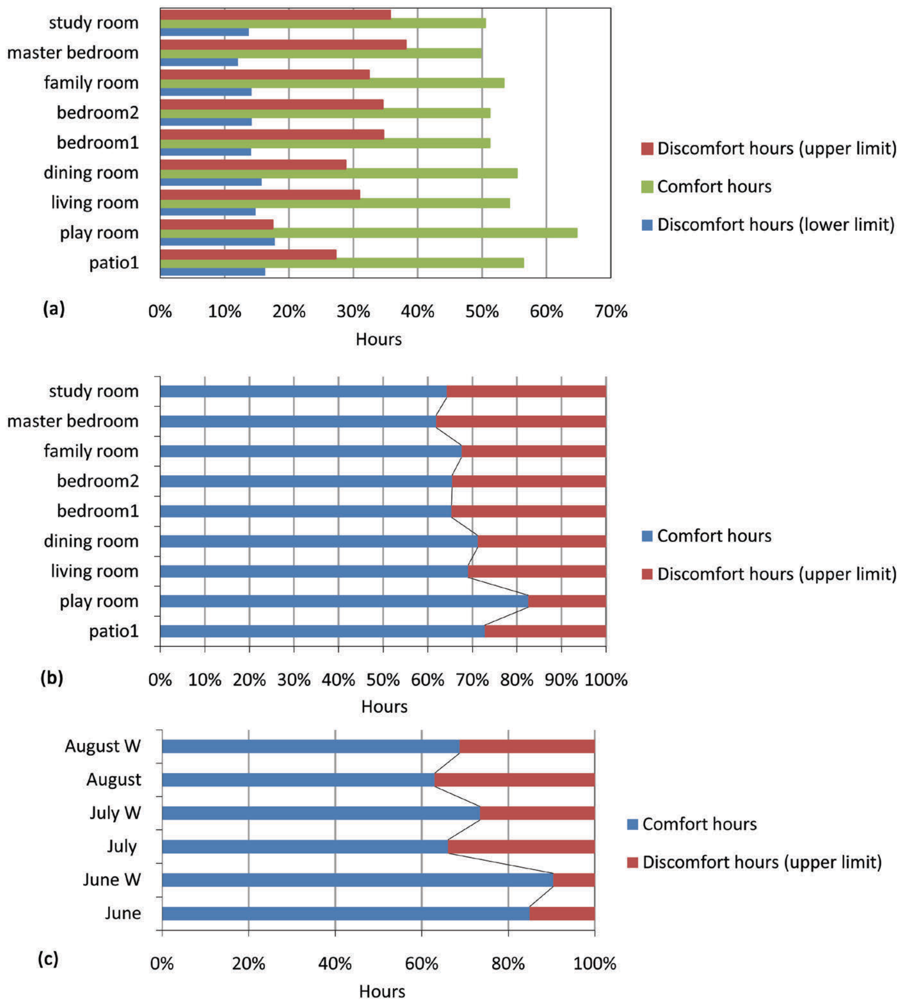

FIG. 6.12 (a) Comparison of the comfort hours and discomfort hours in different spaces (b) Comparison of the comfort hours (hours below lower limit are involved) and discomfort hours (upper limit) in different spaces (c) Comfort hours (hours below lower limit are involved) increasing caused by the wind velocity in the dining room (June, July, August –without wind velocity; June W, July W, August W –with wind velocity)

6.5 Conclusions

In this study, the spatial configuration, building microclimate and thermal comfort of a modern town house were analysed with the help of a field survey, measurements and simulation. The first finding is that the studied house has a varied spatial design, which creates diverse thermal environments in this modern building.

- The general temperature of the building and the peak temperatures in most of the spaces were much lower than the outside weather station reference temperature T_{wst}, during the daytime, especially in the indoor spaces. The maximum difference between reference outside T_{wst} and the temperature in the building was around 9°C.
- There is a diverse temperature distribution in the different spaces of the studied house. The biggest temperature difference was around 8°C. The measured temperature was higher with a higher vertical location. The temperature variation in the outdoor spaces was bigger than in the indoor spaces.
- The temperature in the spaces in the semi-basement remained very low and stable, both in the indoor space and in the outdoor space. For example, the temperature measured on patio1 and patio2 were shown to remain very low during the hottest period of one day.
- The temperature in the outdoor and semi-outdoor spaces was influenced by the orientation and shape of these spaces. Without direct solar radiation, the temperature was maintained at a low level, that was also lower than the reference outside T_{wst} throughout the whole day.
- Significant wind velocity can constantly be obtained in this building. The temperature difference between the bottom and top of Patio1 and patio2 illustrates the potential of stack ventilation. The measured average wind velocity also differs at the various measured points by a maximum of 0.14 m/s.

The second finding is that the microclimate of this particular building can provide considerable thermal comfort for the occupants in summer under local climate conditions. The diverse spatial design also provided the opportunity for occupants to maintain their thermal comfort by means of movement. There are at least 16 different thermal environments in the building. According to adaptive thermal comfort model, thermal comfort is relatively easy to achieve in most of the spaces of this modern house for most of the summer time, in the free-running model. The percentage of discomfort hours during which the temperature exceeds the upper limit of the comfort zone can be limited to 17% in the semi-basement room over the whole summer. Sufficient wind velocity can be achieved, especially in the dining room, by opening the windows and doors to regulate the thermal environment.

However, in the hottest days, thermal comfort cannot be achieved through free-running model so that mechanical cooling or mixed model are needed. In addition, when we consider the adaptive behaviour (for example movement and opening window) of occupants, their living habits should be taken into account.

Comparing this modern house case and our previous study-the vernacular house (Du et al., 2014), some similarities and differences can be found between them. Both of them have diverse spatial design with courtyards, patios, semi-outdoor spaces and indoor spaces. But the volume of the vernacular house is much larger than the modern house. The vernacular house only has one floor, so that the diverse spaces are spread horizontally. However, the modern house has four floors and the diversity extends vertically. The diversity of the thermal environment has the same characters with the spatial diversity. The spaces in the vernacular house are more diverse than the modern house because the size and volume is much larger. The vernacular house is also easier to obtain the cross natural ventilation. The modern house also has its advantages in space. For example, the basement is significant for the diversity of the thermal environment. It can be concluded that we cannot copy the spatial design of the vernacular house, but spatial diversity could be achieved in the modern house design.

There are still some limitations to the present study. The occupants' activities and satisfaction with the thermal environment are absented, as our focus in this case was on the physical thermal environment. Because of the limitations of our measurement instruments, the solar radiation was not measured and the wind velocity could not be obtained in every room. For the thermal simulation, the thermal comfort in the outdoor spaces could not be calculated because of the limitations of the software. Future research will look at the occupants' perception in a particular spatial and thermal environment. How to apply spatial configuration as the design strategy for passive cooling is also the focus.

Acknowledgments

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