13 Conclusion

13.1 Introduction

The main objective of this dissertation is to find the main factors of building spatial configuration that affecting the thermal summer environment, the possibility of occupants to achieve thermal comfort there in, and to propose a spatial design method as the passive cooling strategy for summer thermal comfort. In accordance with the objective, the research questions were put forward in section 1.5 of chapter 1. For every sub-question, there is a respective chapter to answer it, see figure 1.3 in section 1.6 of chapter 1. In chapter 8, some conclusions of part I of this dissertation were summarised. In this chapter, the research questions are answered. In addition, the limitation of this research and recommendations for future practice and research will be mentioned as well.

13.2 Answer to the research questions

The main question of this research is:

What is the relationship between spatial configuration, thermal environment and thermal summer comfort of occupants and how to apply spatial configuration as the passive cooling strategy in architectural design in the early stages?

The main question will be answered by addressing the sub-questions.

13.2.1 Answer to sub-question 1,2 and 3 (mainly chapter 4 and 5)

1. What are the major spatial design characteristics of a Chinese vernacular buildings for passive cooling in hot and humid climate?
2. What are the thermal summer environment features of Chinese vernacular building within a particular spatial configuration?
3. How can occupants achieve thermal comfort in a Chinese vernacular building?

To answer these three questions, a typical Chinese vernacular courtyard house was investigated in a hot and humid climate. In addition, some rural modern houses near the vernacular house were compared with it. The spatial configuration, the spatial boundary conditions, the vegetation in the space and the human activity in the space were analysed for a vernacular house and for modern rural houses. Also, field measurements were conducted to evaluate the thermal summer environment in the vernacular and a modern house. The results of measurements were compared with a dynamic thermal and a CFD simulation in the vernacular house as well. The results show that the most important spatial design characteristics of the vernacular house are spatial diversity and a suitable spatial configuration. The vernacular house combined different kinds of spaces, while the modern house's spaces are simple. Indoor space, semi-outdoor space and outdoor space are the basic space types which are broadly used for the spatial diversity in the vernacular house. Courtyards and patios are the core components for the spatial configuration of the house which is surrounded by corridors and indoor spaces. Every indoor room is adjacent to a patio or corridor, instead of being directly exposed to the outside environment. The diverse spatial design and the suitable spatial configuration make the thermal summer environment of the vernacular house much better than the modern house. The vernacular house has its own "building microclimate", which is in accordance with the main character of microclimate in terms of different distributions of solar gain, air temperature and wind velocity in different spaces. "Building microclimate" can help to create comfortable thermal conditions for the occupants in summer, especially in hot and humid climate areas. The essence of architectural bioclimatic design is to understand the local climate and utilise appropriate spatial design strategies to create or modify the building microclimate required for a comfortable living environment. The contribution of the "building microclimate" lies in two aspects: first, the temperature in the "building microclimate" could be lower than the outdoor environment. Second, related to different spaces, the "building microclimate" provides different thermal environments and different thermal sensations of occupants. The "building microclimate" is important for occupants' thermal comfort under the free-running model of the vernacular house. The diversity in spatial configuration and thermal environment make it possible that the occupants can choose their preferred space and thermal environment to achieve relative

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thermal comfort. A “Building microclimate” provides this opportunity by taking into account all spaces (indoor, semi-outdoor and outdoor) of a single building.

13.2.2 Answer to sub-question 4 (mainly chapter 6)

4 Is it possible to convert the spatial design strategies found in Chinese vernacular buildings to the modern house design?

To answer this question, a modern house with spatial diversity in a hot and humid climate was investigated to clarify the relationship between spatial configuration, building microclimate and thermal comfort. Firstly, 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 the building. Under the local climate conditions, the microclimate of this specific building could provide considerable thermal comfort for the occupants in summer. This case study shows that it is possible to obtain a building microclimate through spatial configuration, not only in vernacular buildings but also in a modern building design. Diverse spaces and environments are valuable for an occupant’s thermal sensation in hot and humid climate regions. In modern architectural design, spatial design is not just for aesthetics, function and landscape, but also for the building microclimate and performance, and especially for the thermal performance. Eliminating spatial diversity results in a lack of appropriate building microclimate and thermal performance. This case is an example even though the modern house is different from the vernacular house. Because the life model is different, spatial configuration can be as one of the major passive cooling strategies to achieve thermal summer comfort of occupants.

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13.2.3 Answer to sub-question 5 (mainly chapter 7)

5 What is the relationship between the occupants' spatial and thermal perception?

Studying the relationship between the spatial environment and the way the spatial environment is perceived can yield important insights into the way architectural design can create more comfortable living environments. Spatial openness is an important spatial perception that was studied in chapter 7 to find the correlation with perception of comfort (visual, wind speed and thermal) in people's minds. There is a common sense for the occupants who live in the hot and humid climate that thermal comfort perception in people's minds is related to the spatial openness. The investigation was based on a questionnaire of 513 local Chinese college architecture students in 2015.Five different spatial environments with different spatial openness were described in writing, such as indoor space, semi-outdoor space, outdoor space, a room with a large operable area and a room with a small operable area. The three perceptions were visual perception, thermal perception and wind perception. For the different spatial environment, the comfort perception over the day was also investigated. A similar questionnaire was given to Dutch architecture students, but the results were inconclusive due to the low number of responses. The main findings are: a. spatial openness of a particular space significantly affects occupants' visual perception, wind speed perception and thermal perception. b. There is a strong effect between spatial openness and visual and wind perception; the effect of the thermal perception is weaker. c. The comfort perception is strongly influenced by the time of day; therefore, visual perception, wind perception and thermal perception can influence occupant movement between different spaces as is the advice of the adaptive thermal comfort.

13.2.4 Answer to sub-question 6 (mainly chapter 9)

6 Is there a potential to use spatial indicators to predict the ventilation performance for thermal comfort in the early design stages?

To answer this question, a case study was performed in chapter 9. In chapter 9, the author investigated the correlations between the spatial indicators connected with architectural design and the building physics indicators ventilation performance and energy performance. The main objective is to explore the potential of applying spatial indicators using space syntax to predict ventilation performance and energy performance in order to support architects for the evaluation of their concept and schemes in early design stage. The layout of a high-rise apartment in China in five different cities is chosen as a case study. The results show that the selected three indicators– connectivity value, air change rate and annual cooling saving rate – are linearly correlated, not just at the building level but also at the room level. R^2, the correlation coefficient of determination is between 0.53 and 0.90. Although there are many limitations as mentioned above, this study reveals the potential to use the spatial indicator to predict the airflow performance and even the energy performance in the early design stage. Even though the prediction maybe rough, it is meaningful for the early design stage of the architectural design because some advantages can be achieved: saving time, ease of use, a visual result and a multi-objective prediction.

13.2.5 Answer to sub-question 7 (mainly chapter 10,11,12)

7 How can a space design method be used in the design practice?

To answer this question, the space syntax method was extended for the analysis of the natural ventilation potential. A rural house design in a hot and humid climate was chosen as the case study. The rural house was chosen because it is a free-running model, which is different from an urban house and more suitable to adopt passive cooling strategies for thermal summer comfort of occupants. The extended space syntax method was first used to evaluate a number of rural residential buildings in the studied area proposed by the government. The advantages and disadvantages of the proposed houses in terms of spatial configuration were studied.

Secondly, the extended space syntax method was used to improve the optimised house proposed by the local government towards a new rural house design. The goal of the improvement is to provide more diverse spaces for the occupants to choose, enhance the cross ventilation. The design method and process were proposed in chapter 12. From the initial design to the final design, the main steps in the design process are: decoding the layout, identify the public spaces, evolution of public and other spaces, identify all spaces, adjust connections with outdoor environment, identify the detail size and location of all rooms, add outdoor spaces and evaluation using the extended space syntax method. The improved house design provides more public spaces for the occupants, both on the ground and the first floor. This enhanced the diversity of the living spaces. As concluded in chapter 5, the local occupants would like to stay in the more open spaces during summer; the improved house gives this opportunity to the occupants. From the spatial analysis, it can be concluded that the accessibility and openness of the improved house and the major public rooms is better than the houses proposed by the local government (the ground floor). As concluded in chapter 10, the high accessibility and openness mean a high potential to achieve natural cross-ventilation. The occupants' living habits show that the occupants perform most of their activities in these spaces as well. Therefore, it can be concluded that the indictors in space syntax analysis not just reflect the occupants' movement behaviour but also show the occupants' preference of spaces and how long they would like to stay. The fundamental idea of space syntax theory is to find the relationship between the spatial configuration of city or architecture and the underlying human behaviour and social meaning. The kind of human behaviour-movement –is well explained in spatial configuration analysis especially in the urban scale. In this study, it was found that movement is not just a means to pass through, but also means the preference to stay. In these case studies, it was found that the occupants' movement behaviour model can be matched with the air movement behaviour. This means that the spaces that the occupants prefer to stay in are the spaces that have a high potential to obtain natural ventilation. The CFD simulations in chapter 12 proved that the extended space syntax method can evaluate and predict the airflow behaviour in the early design stage. The extended VGA analysis method is easy to use in design practice.

However, there are still some limitations of the space design method for passive cooling in the design practice. Architectural design is a complex process and is influenced by complex factors. For example, for the bedrooms, privacy is an important factor for the space design. Enhancing the openness or accessibility of these private spaces is difficult. Other design strategies, such as improving the insulation and shading of the walls, can be used for passive cooling as well.

13.3 Conclusion of findings

The main findings of part I were described in chapter 8. The concept of "building microclimate" was identified. Also, the importance of spatial diversity and spatial configuration for building microclimate and occupants' movement for adaptive thermal comfort were found. The relationship between the spatial perception and adaptive thermal comfort was revealed.

The main findings of part II are the potential of using spatial indicators to predict the airflow performance of buildings. The new application of the extended space syntax method is proposed to help architects and designers in designing a modern building that is thermally more comfortable and that has a lower energy demand.

13.4 Limitations of this research

In chapter 4, 5, 6, 8, 9, 10, 11 and 12, the limitations of the specific studies have been mentioned in the discussion or conclusion parts. Below is the summary of the limitations of this research.

Measurements

The measurements were performed in a vernacular house, a rural house and a modern urban house. The main parameters related to thermal environment and adaptive thermal comfort – air temperature, relative humidity and wind velocity – were obtained. However, because of the limitations of the equipment, some of the measurements were imperfect and some of the parameters were missing. Firstly, the outdoor environment near the measured houses was not measured completely because of a lack of micro-climate stations. This limitation influenced the accuracy of the simulation results because we cannot use the accuracy climate data near the houses to do the simulations. Secondly, the measurement time was several days, which was not so long. This could miss some information compared to a long-period monitor. Thirdly, the difficulty to measure the wind velocity. A manual anemometer was used to measure the wind velocity. It is difficult to measure the wind velocity for a long time and to measure more points. Sometimes the indoor wind velocity was small, which caused inaccuracy of the measurements. Fourthly, some measurement parameters were missed, for example the radiation measurement. In addition, the houses were measured without occupants. Therefore, the influence of occupants on the thermal environment is missed.

Simulation

The thermal environment of the studied cases was simulated by the software of Designbuilder. The climate data used was from the database of Energyplus. Even though the selected climate station of the database in the area studied is close to the studied house, which maybe also caused some inaccuracy of the simulation. To avoid the inaccuracy, most of the simulations were validated by the field measurements in this research.
Another limitation of the software is that the inability to simulate the outdoor environment. Therefore, some assumptions and simplifications were made for the outdoor spaces and semi-outdoor spaces in the simulations.

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The spatial analysis of the cases was performed in Depthmap. This software was designed for the spatial configuration analysis, especially for occupant movement behaviour in a particular building layout. The author assumed the program also has the potential for air movement analysis. Therefore, there are some limitations of the software used for the air movement analysis. This caused inaccuracy of the simulation results, which might decrease the correlation value between the spatial indicators and airflow parameter. This detail was discussed in chapter 9.

Questionnaire

The questionnaire was used for the investigation of the occupants' spatial perception and thermal environment perception. The investigation was performed through asking questions in texts of students, which had some limitations because the subjects cannot feel the real scene. Two groups of subjects were asked questions, but there were not enough responses from one group. The comparison of different subjects was missing. Asking the questions may cause dispersion of the answers because of spatial perception related to 3D space.

Comfort standard

The adaptive thermal comfort theory was applied to evaluate the thermal comfort of occupants. The theory was studied in the studied area and some equations for comfort temperature calculation were proposed. However, the equation was not proposed in the local design standard for thermal comfort evaluation. As mentioned in section 2.1.6, the adaptive prediction mean vote was put forward in the standard. Therefore, the equation proposed by the local researcher or by ASHRAE was applied. That might be not so authoritative or very suitable for local occupants.

13.5 Recommendations for future research and development

For future research, the following three topics related to spatial design and passive cooling are recommended:

Building microclimate related topics

The concept of "building microclimate" was first identified in this dissertation. The function of building microclimate for passive cooling is the integration of different passive cooling techniques, such as solar control, thermal mass, evaporative cooling and natural ventilation. This research focused on the contribution of spatial diversity to building microclimate. Future research should pay attention to other factors that can influence the building microclimate in. For example, garden design in the courtyard and patio, and material use as thermal mass are significant to cool the environment. This has been found in the vernacular houses. How to integrate all the aspects to create a good building microclimate in summer is a big issue to discuss. Furthermore, the scale of building microclimate should be studied to distinguish from the urban microclimate. The relationship between urban microclimate and building microclimate should be studied deeply as well. To perform these studies, more detailed measurements and suitable simulation methods should be done for more cases.

Spatial perception and thermal environment perception

The occupants' thermal comfort is strongly related to their perception. Perception is a series of processes in which consciousness perceives, senses, pays attention to and perceives external and internal information. It includes both physiological and psychological processes. In architectural design, the occupants' spatial perception is one of the most important factors to evaluate the spatial design. Spatial perception can influence occupants' behaviour. Some results drew conclusions about the relationship between spatial perception and human behaviour in the research field of architectural spatial perception. In the research field of thermal comfort, a lot of studies focused on the relationship between occupants' thermal comfort and behaviour. However, research about the relationship between the spatial perception, thermal perception and human behaviour is rare. This topic is valuable as topic for deeper studies, because it is important for both spatial design and thermal comfort. Some new research methods could be used for this study. For example, VR (virtual reality) technique can be used for a study of the occupants' visual perception, which is one of the most important spatial perceptions.

Integrated spatial design method for human behaviour and airflow analysis

This research found that there is a correlation between the spatial indicators and airflow parameters and that there is potential to apply the spatial analysis method to analyse the airflow behaviour. However, because it is a new research field, this research is just a preliminary attempt. For example, some spatial indicators: connectivity, integration, mean depth, isovist area and perimeter were explored for the correlation study. It was found that all of the indicators are associated with the airflow parameters. However, which one is the best? It should be investigated in further research. More cases are also needed to be investigated and the underlying mechanism of the correlation found should be revealed by numerical analysis.

In this research, it is also proposed that the spatial indicators not only reflect the movement behaviour but also reflect the time of stay and the preference of occupants. The spatial analysis in space syntax can foresee more functional outcomes related human behaviour in an urban or an architectural environment. It is an interesting topic for further study.

The findings in this research are also valuable for the study in an urban scale. As we know, the urban wind environment is much complex than the building scale and the prediction is still difficult. The simulation of the urban wind environment always means huge computing resources, huge time consumption and high costs. If the proposed methods in this research can be used in the urban scale, it can help the urban planner to predict the preliminary wind environment and understand people's behaviour in the city. The public spaces of the city can be set at suitable places where people can get more natural ventilation for comfort. Therefore, this study could be used for the urban scale in the future.

Other spatial analysis methods are also worth exploring if they have the potential to predict the airflow behaviour. Furthermore, an integrated computer program might be developed for both the spatial and airflow analysis.

13.6 Value of this dissertation

This research has some innovative findings in the cross disciplines of architectural spatial design, passive cooling and thermal comfort. Some ideas are first proposed in this research. The findings and new ideas have social, scientific and engineering implications. This research can contribute for the sustainable development of Chinese building construction. It can help the residential building design for occupants with low and medium incomes by decreasing the use of air conditioning and improving the living environment for thermal comfort as well. This research is also valuable for the passive or zero energy house design in the Netherlands and the European Mediterranean area. This research will enrich the green building science by introducing the theory and the applications for adaptive thermal comfort, principles of passive cooling by means of spatial design. In the architectural design practice, the proposed design method can be developed for application in projects.

APPENDIX A

Questionnaire

日期Date	2015年10月12 日		
地点 Location	重庆Chongqing		
性别Gender:		A / 男Male	B / 女Female
年龄（17-25之间）Age (Between 17 and 25)		A / 是Yes	B / 否No

请在以下你满意的选项打钩：

1 你对本地夏季气候总的感受是
How do you generally feel in the local climate in summer? (Please tick only one)

A / 较凉爽Slightly cool	B / 不冷不热Neutral	C / 较热Slightly warm	D / 热Warm	E / 很热Hot

2 你对本地夏季风环境总的感受是
How do you generally feel in the local wind environment in summer? (Please tick only one)

A / 没有风No wind	B / 风速较低Low speed	C / 风速较高High speed	D / 风速很高Very high speed

3 对于你现在居住的房子, 你最想改变的是
Which of the following changes would you like make to your living space at home?

A / 增加窗户可开启面积 Increase operable window size	E / 减小窗户可开启面积 Decrease operable window size
B / 让客厅更开敞,视野更开阔 Make the living room opener	F / 让客厅更封闭 Make the living room more enclosed
C / 设置阳台或露台（或增加面积） Add a balcony or terrace	G / 去掉阳台或露台（或减小面积） Remove a balcony or terrace
D / 设置庭院或天井（或增加面积） Add a courtyard or patio	H / 去掉庭院或天井（或减小面积） Remove a courtyard or patio

4 在夏季, 你是否觉得本地传统民居比现代住宅更凉爽？
In summer, do you think it is more comfortable in the local vernacular house than in the modern house?

A / 是Yes	B / 否No

5 在夏季, 如果没有空调, 你对以下空间的视觉感受是
What is your opinion of the visual perception in the following spaces (without air conditioning) in summer?

	视觉感受Visual perception		
	A / 视野, 景观好 The view is good	B / 视野, 景观一般 Neutral	C / 视野, 景观不好 The view is not so good
5.1/ 室内空间(一般的房间如卧室, 客厅等) Indoor space			
5.2 / 半室外空间 (外廊, 门廊, 阳台, 亭子, 花架下等) Semi-outdoor space (porch, outside corridor, balcony)			
5.3 / 室外空间 (庭院, 天井等) Outdoor space (courtyard, patio)			
5.4 / 开了大面积窗户或洞口的房间 A room with a large operable area			
5.5 / 开了较小面积窗户或洞口的房间 A room with a small operable area			

6 在夏季，如果没有空调，你对以下空间的热感受是
What is your opinion of the thermal perception in the following spaces (without air conditioning) in summer?

	热感受Thermal perception					
	A / 冷 Cool	B / 较凉 Slight cool	C / 中等 Neutral	D / 较热 Slight warm	E / 热 Warm	F / 很热 Hot
6.1/ 室内空间 (一般的房间如卧室，客厅等) Indoor space						
6.2 / 半室外空间 (外廊, 门廊, 阳台, 亭子, 花架等) Semi-outdoor space (porch, outside corridor, balcony)						
6.3 / 室外空间 (庭院, 天井等) Outdoor space (courtyard, patio)						
6.4 / 开了大面积窗户或洞口的房间 A room with a large operable area						
6.5 / 开了较小面积窗户或洞口的房间 A room with a small operable area						

7 在夏季，如果没有空调，你对以下空间的风环境感受是
What is your opinion of the wind environment in the following spaces (without air conditioning) in summer?

	风速Wind speed perception				
	A / 很低 Too low	B / 低 Low	C / 中等 Neutral	D / 高 High	E / 很高 Too high
7.1/ 室内空间（般的房间如卧室，客厅等） Indoor space					
7.2 / 半室外空间（外廊，门廊，阳台，亭子，花架下等） Semi-outdoor space (porch, outside corridor, balcony)					
7.3 / 室外空间（庭院，天井等） Outdoor space (courtyard, patio)					
7.4 / 开了大面积窗户或洞口的房间 A room with a large operable area					
7.5 / 开了较小面积窗户或洞口的房间 A room with a small operable area					

8 在夏季，如果没有空调，你喜欢呆在以下的什么地方Where do you prefer to stay in summer (without air conditioning)?

8A

	A / 室内空间 Indoor space	B / 半室外空间（外廊，门廊，阳台，亭子等）Semi-outdoor space	C / 室外空间（庭院，天井等） Outdoor space	D / 没有倾向 No preference
8A.1/ 早上Morning (9:00-12:00AM)				
8A.2/ 下午Afternoon(13:00-5:00PM)				
8A.3 / 傍晚Evening (7:00-10:00PM)				
8A.4 / 晚上Night (0:00-8:00 AM)				

8B

	A / 开了大面积窗户或洞口的房间 A room with a large operable area	B / 开了较小面积窗户或洞口的房间 A room with a small operable area	C / 没有倾向 No preference
8B.1 / 早上Morning (9:00-12:00 AM)			
8B.2 / 下午Afternoon (13:00-5:00 PM)			
8B.3 / 傍晚Evening (7:00-10:00 PM)			
8B.4 / 晚上Night (0:00-8:00 AM)			

8C

A / 一个有较好视野和景观的地方A place with a good view	B / 我不在乎视野和景观的好坏I do not care about the view

8D

A / 一个有开阔视野的地方The room has a broad view	B / 我不在乎视野的开阔与否I do not care

8E

A / 没有风的地方 A place with no wind	B / 有较低风速的地方 A place with low speed wind	C / 有较高风速的地方 A place with high speed wind	D / 有很高风速的地方 A place with very high speed wind

9 你对以上问题有什么建议吗Do you have any comments about this questionnaire?

谢谢! *Thank you!*