AN INVESTIGATION OF THE ADAPTIVE THERMAL COMFORT RESEARCH FOR RESIDENTIAL BUILDINGS IN CHINA ‘HOT SUMMER AND COLD WINTER’ ZONE

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A Thesis submitted in fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Architecture

School of Architecture

The University of Sheffield

October 2013

For my dear parents and lovely wife,

Thanks for your patient love and your warming support

献给我亲爱的父母和可爱的妻子，

感谢你们如此耐心的爱和贴心的支持

ABSTRACT

China's residential market has been booming since the time of the early twenty-first century, with an industrial structural transformation from quantitative to qualitative development. China's climate variability creates a unique relationship between occupancy and building environment, requiring thermal environmental comfort research and energy efficiency residential building context. The aim of this research is to improve low-energy apartment standards in China using multidisciplinary interactive research directly focused on actual occupants' thermal comfort under the regional climatic conditions and applying adaptive thermal comfort theory. This PhD research is based on field study of a questionnaire survey and on-site measurement. The actual building environment assessment presents the research gap of adaptive coefficient between rational thermal approach and adaptive thermal approach.

The heat-balance approach of Fanger's 'Predicted Mean Vote' (PMV) comfort model is usually incorporated into the 'Predicted Percentage of Dissatisfied' (PPD) model. The adaptive approach of 'adaptive Predicted Mean Vote' (aPMV) model is based on Yao's research, taking into account factors such as psychological and behavioral adaptations. There are three main conclusion sections in this thesis, including regional adaptive thermal comfort research, occupants' subjective adaptive preference and parametric study of building design in the 'Hot Summer and Cold Winter' (HSCW) zone. Six conclusion points are extended: (1) According to the questionnaire-based survey, overcooling causes serious concern for thermal comfort in cold winters in the HSCW zone, which is similar to the overheating potential of the worst energy consumption impact during hot summers in residential buildings. (2) The specific adaptive coefficient is necessary for obtaining regional adaptive thermal comfort temperature ranges with neutral indoor air temperatures assessment. (3) The occupants' personal characteristics and social backgrounds; the statistical analysis suggested that a person's age, gender, education level and building layout environment strongly relate to the control of indoor acceptable air temperature, and the margin limit of thermal comfort also has a strong relationship with the weather data of monthly outdoor air temperatures. (4) Adaptive thermal environment control have increased energy usage compared to energy efficiency control, but is lower than current healthy housing standards of energy consumption. (5) The question of decreasing the building shape coefficient does not has a decisive effect for energy conservation, and the building performance of energy consumption per unit indoor floor area has a significant impact on energy savings. (6) The parametric analyses also suggested that the subjective nature of people participating has a great influence on the relationship between objective building design and building performance results.

ACKNOWLEDGMENTS

I am deeply indebted to many people who have contributed to my research and studying time in Sheffield. Thank you for your warming support through this challenging life experience and for always accompanying me.

Greatest thanks are due to Dr. Hasim Altan for your supervision and support in my PhD study from the first day of my PhD application. I deeply appreciate how you always present your passions for building science research. Thank you for gearing me up for the difficult work of field study, statistical analysis and so on. We work together as though playing football on the ground; you pass the ball, providing an opportunity for my scoring finish. Without your help I would not have had such a strong spirit to face the big challenge of PhD study. Professor Jian Kang is my second supervisor - I shall give you my great respect. You provided a real philosophical direction for the purpose of PhD study. I know you are brilliant professor. I understand your professional research attitude and remember your directions for the research method. I will never forget you.

I would also like to pass my gratitude to Professor Steve Sharples who is my Masters supervisor and introduced me to sustainable building research. I still remember the conversation we hadat Nottingham University when you had moved to Liverpool University. I regret that we have not worked together in Sheffield in the past few years but am happy to hear you have a new challenge there. Thanks to Dr. Youngki Kim and Dr. Dazhi Jiang for your patient help on the simulation work of DesignBuilder and MATLAB program edition. Thanks to Derong Kong for your passion for architectural research. It is very interesting to discuss building development in today’s China with you. Thanks to Bo Wang for your warming support for my literature collection and always sharing your interesting ideas with me. I enjoyed the drinking time with you. Thanks to my dear friends in my UK family; Dr. Xiaofeng Li, Dr. Nan Guo, Dr. Rui Sun, Yiying Hao, Yuan Tian, Lei Luo, Like Jiang, Yang Yu, Biao Yang. Thanks are also given to my friends, colleagues and all who contributed to this study.

Special and forever thanks are given to my parents and my wife’s parents; with your love, understanding, support and encouragement I have the courage to fight to the end and never give up. Finally, I shall give my one-hundred percent love and thanks to my lovely wife, Linlin Gan, for your endless love and patient companionship.

CONTENTS:

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 ADAPTIVE THERMAL COMFORT RESEARCH IN CHINA HSCW ZONE

CHAPTER 5 OCCUPANTS' SUBJECTIVE ADAPTATIVE PREFERENCE FOR THERMAL PERCEPTION IN RESIDENTIAL ENVIRONMENTS

CHAPTER 6 PARAMETRIC STUDY OF SIMULATION WORK FOR RESIDENTIAL BUILDING PERFORMANCE

CHAPTER 7 CONCLUSIONS

LIST OF FIGURES:

LIST OF TABLES:

CHAPTER 1 INTRODUCTION

1

1.1 INTRODUCTION

This chapter aims to give a starting point for building environment research, and specifically the conflict between occupants' thermal comfort and building energy performance. The motivation of this research work is to utilize an interdisciplinary relationship, with the main aim being to build better living conditions with energy saving approaches for the construction of new residential buildings in China's specific climatic zone. The first section explains the framework of the research aims and methods, and also provides a structure for the entire thesis.

1.2 MOTIVATION OF THE RESEARCH

To satisfy various customers' living demands, urban planners, building architects, civil engineers, building researchers, investors and the governmental agencies at all levels are paying much attention to building improvement. Their contributions have been pushed forward with Chinese dynamic urbanization, and considerable aesthetic building design has provided reasonable inter-space use. Better daylight has been obtained by designing larger building glazing areas and more effective home equipment with a high-energy conversion ratio. However, the fact remains that we do not know if they are suitable for indoor thermal comfort, or how reasonably energy is used for heating or cooling against the discomfort of seasonal weather stimulation. As the construction of Chinese residential buildings which have high levels of indoor environmental quality increases, energy conservation requires reasonable methods to maintain the balance of long-term housing post-construction maintenance within healthy and comfortable living demands. There needs to be more understanding and recognition of occupants' participation mechanisms for indoor environment adaptation. As the question of how a high quantity of energy used in residential buildings would last in the coming 30-50 years under conditions of worldwide energy shortages becomes more urgent, the answer lies in utilizing residential building environment research with subjective sensation cognition and objective environment control. Therefore, low-energy residential building should be primarily based on the indoor thermal comfort with correct understanding.

Working through the literature review, many thermal comfort studies have been merged with expertise from different disciplines, combining their knowledge with extensive field study, monitoring, data collection and analysis, statistical research, layout design, and software modeling. This is defined as an integrated solution of practical research with classic theory.

Firstly, it is necessary to research reasonable low energy buildings that deal with the problems caused by global warming and energy shortage (IEA 2008; IPCC 2007). In the past few years in China, increasing energy savings has been the first goal of the national building strategy for indoor environment design and the related residential building legislation. Considerable research has been carried out concerning energy saving for residential building design, construction and operation (Cai et al. 2009; C. Chang et al. 2011; Kong et al. 2012; J. Yao and Zhu 2011; J. Zhao et al. 2012). The Chinese building design code or standard established a low level of indoor thermal environmental controls for thermal comfort consideration. The concept of a ‘comfortable’ home usually refers to the construction of a luxurious thermal environment design. In fact, there is a ‘reasonable’ way to balance the conflict between indoor thermal comfort and energy saving. Building performance studies have become important for indoor thermal environment research and building energy efficiency issues. Increasingly more building research has been taking into account people’s participation, behavior adjustment and their subjective psychological specifics. A detailed literature review will be presented in Chapter 2.

Secondly, a booming Chinese housing market has seen a high percentage of the residential building sector become largely social property.(Ling and Hui 2013; Zhou Yu 2006; M. Zhang and Rasiah 2014) However, although the building materials for insulation have been improved for energy conservation compared with the level of 1980 building construction (Bojic et al. 2001; H. Yang et al. 2000; J. Yu et al. 2009a, 2009b; Zhu et al. 2011), the quality of current residential buildings still needs more detailed research into building performance, building environment parametric design and building environment psychological study. This is the new direction of the building industry revolution for precision fabrication and new production for building environment comfort control.

Thirdly, China is a vast country with variant weather conditions. Building indoor environment control and energy consumption each have a strong relationship with the climatic physical stimuli. Therefore, building environment research ought to consider the regional climatic differences. This research aims to narrow down the study of the Chinese residential building environment in a special climatic zone named the ‘Hot Summer and Cold Winter’ (HSCW) zone. In this climatic zone, overheating is the main potential problem for indoor thermal environment comfort demands, though potential overcooling problems are also becoming an issue for the occupants of this zone. These disparate temperatures are presented as the historical reason the HSCW zone does not have a conventional heating infrastructure like that in the north of China. The wet, cold winters require heating facilities, and increased occupancy demands of indoor thermal comfort increase the need for building environment research. Therefore, overheating and overcooling are two thermal comfort issues that need to be dealt with in this climatic zone.

Fourthly, the Chinese national and local state governments have implemented state energy conservation targets and new requirements of residential building environment. Low-energy housing programs and regional building design standards have been launched to respond to the pressure of the energy efficiency strategy. As the development of Chinese dwellings upgrade, the energy saving target of 50% reduction in new buildings (compared with the level in the duration between 1980-1981) has been clearly established in the last national development strategy of the 11th ‘Five-year Plan’ (2005-2010). However, the mandatory practical fitting ratio is unfortunately about 23% of the urban area. A higher tension of energy saving is established for the detailed discussion in the 12th ‘Five-year Plan’ (2011-2015).

1.3 RESEARCH SCOPE

Firstly, this PhD research is focused on residential building performance and its potential conflict of energy conservation issues and occupants’ thermal comfort demand. This is a comprehensive topic in debates throughout the world over the last three decades. (Surat Atthajariyakul and Lertsatittanakorn 2008; Hwang et al. 2009b; Hwang and Shu 2011; Leung and Ge 2013; Pan et al. 2005) The building environment is a description of indoor physical space and subjective perception assessments (acoustic, lighting and thermal), which are defined as the building sustainability importance factor (Alnaser et al. 2008; Berardi 2013; GhaffarianHoseini et al. 2013). As the related researchers state (Pérez-Lombard et al. 2009; Poel et al. 2007; S. Wang et al. 2012), the energy consumption of building maintenance is usually over 40% of total energy use, and half aim to restore the indoor thermal environment comfort for heating or cooling. It is indicated that a healthy and comfortable indoor environment has a strong relationship with energy consumption (Doroudiani and Omidian 2010; Gugglberger and D √ ºr 2011; Ho et al. 2008; Issa et al. 2010). This research is going to pay attention to the defining of the residential building indoor thermal environment comfort, which is a key point in legislating a reasonable energy saving policy and practice validation.

Secondly, according to recent research, thermal comfort is not only based on the objective physical environment and building design, but also includes the psychological impact (Bachmann and Myers 1995; W. Liu et al. 2013; Ryd 1991; Winett and Neale 1979) and environmental perception of indoor activities (Hoes et al. 2009; Virote and Neves-Silva 2012; R. Yang and Wang 2013; Zhun Yu et al. 2011b). The practical building environment research is not based on the lab environment of a stable chamber. It is based on an actual residential building environment with complex and dynamic site study. For example, the occupant has a subjective perception and their living experience is linked with outdoor seasonal climate effects. Adaptive thermal comfort was launched in the practical field study for natural ventilation of a free-running building environment. However, residential building environments in the HSCW zone are usually controlled with a mixed mode of a HVAC system supplemented with natural ventilation adjustment. Two cases are selected as examples of typical prototypes of local residential building indoor space design. Moreover, the adaptive thermal comfort research on Chinese buildings relates more to offices, classrooms and other public buildings in the HSCW zone, which are free-running buildings with simple respondent participation. However, the family occupancy provides compound research samples with different building thermal environment perception and sensation preferences. Therefore, this research is an extension of the current related research and aims to discover the specifics of regional thermal comfort.

Thirdly, this PhD research is focused on the Chinese urban living background. It is well known that the Chinese national economy has made huge developments since the starting year of 1978. The state policy of ‘reform and open’ stimulated the China housing market. That booming urbanization process would lead us to rethink the development strategy, and the new stage of urbanization is to improve the quality of these achievements in the next 10-20 years (G. H. Chang and Brada 2006; M. Chen et al. 2013). The Chinese government is encouraging the building industry revolution to become more energy saving and environmentally friendly. The urbanization processes of residential buildings make them the largest energy use sector for building maintenance. There are more green building approaches that can be applied for high level new residential buildings in today’s China, such as the research of solar panels (Z.-S. Li et al. 2007). There is more detailed research into building environment design for the Chinese new urban construction.

Fourthly, the building performance research has a strong relationship with regional weather conditions. China covers an extremely large area with many weather types separated into seven climatic zones, and different external stimuli have different thermal design strategies for cooling and heating. The HSCW zone is a regional name in China and has a unique thermal design code for civil buildings, which in total equals the III climatic zone. This is located in the central part of China and belongs to the moderate area neighboring the colder north China and the warmer southern regions of China. This middle part of China is a relatively less developed area, but it still contains the living building revolution for urbanization development. The residential problems in China’s developed parts provide practical experiences to promote the residential building investigation started in the HSCW zone. This could be positive for further development.

The research is confirmed in the HSCW climatic zone for two typical Chinese residential apartments with different prototypes. They are both located in Yichang city, which is a central part of China. Because of the large scale of the HSCW zone including 16 provincial districts (the total area is about 1.8 million square kilometers), it is difficult to perform field studies in each big city with different climatic situations. In this research, the site study is located in a specific weather classification area that is different from the other area of the HSCW zone. That will be explained in a later part of this thesis.

1.4 RESEARCH QUESTIONS, HYPOTHESIS, AIM AND OBJECTIVES

Taking into account the regional limitations and current related situations of the building environment, the research questions of this PhD study will be proposed for the research. The main research question is, '***What is the best way to investigate the thermal comfort potential of Chinese low-energy (energy efficient) apartments in the HSCW zone?***' Key sub-questions of the problem are listed below:

- Research sub-question one:
  Can the indoor thermal comfort be achieved with current energy efficient buildings located in the HSCW zone of the China?
- Research sub-question two:
  What is the occupants' actual indoor thermal comfort for residential buildings in the HSCW zone of the China?
- Research sub-question three:
  How to achieve a balance between indoor thermal comfort demand and energy conservation issues?
- Research sub-question four:
  Is there any potential weakness in improving the related building environment design of energy efficiency building and healthy housing in the China?

In accordance with the questions above, we can make a hypothesis of this study and that is:

For the residential building environment in the HSCW zone of China, there is a regional thermal comfort preference. This regional preference can deal with the practical potentials of actual indoor thermal comfort and energy conservation issues. Accordingly, the aim of this research is to improve the low-energy apartment standard in China and to build better living conditions with energy saving approaches for the new construction of residential buildings in China’s HSCW climatic zone. This will be achieved through the following objectives:

- To survey whether overcooling problems have similar significance with the overheating potential with a thermal discomfort in specific area of China’s HSCW zone;
- To conduct an actual thermal sensation study that can show the strong relationship with regional preference;
- To survey the HSCW zone’s regional adaptive thermal comfort band with the neutral air temperature which provides reasonable technical support for indoor environment control;
- To survey subjective thermal sensation acceptability for different building layout designs;
- To survey occupants’ psychological adaptation preference, which has a regional thermal culture specific and mathematical relationship, and that can provide a direct method for indoor acceptable thermal comfort definition within regional climate situations;
- To study building thermal performance that could reveal the balance between regional indoor thermal comfort and energy efficiency issues for residential building;
- To conduct a field study which would provide an opportunity for parametric analysis of further supplement for the current Chinese residential building designing standard.

1.5 RESEARCH METHODOLOGY

The research of building environments is based on a multi-strategy research framework from an integrated perspective; specifically, a national level of building industry development strategy, regional building environment design standard and technical criterion, practical building environment operation and individual occupancy schedules. Therefore, the research methods shall include various approaches according to these specific features and desired outcomes linked with the core research mentioned above.

The first methodology is based on a wide literature review, which is a theoretical study and research context of the multidisciplinary development. The thermal comfort research is started from steady-state heat-balance theory in a laboratory test environment, and classic empirical equations are important for the basis of later research. The extensive research of classic heat theory is concerned with the actual thermal comfort issues based on positive adaptation by an individual’s physiological and non-physiological thermoregulation preference. There are some field studies that have been launched in a range of countries with different weather conditions and climatic zone classifications. Therefore, the related researchers present their results and view point for the diversity of building environment control and different strategies for thermal comfort. Some international thermal standards and some regional recommended benchmarks have provided a basic framework for further research work and international standards. The Chinese government has also published a residential building design code and regional (HSCW zone) standard of energy efficiency for residential building which provides a research foundation and research background, and some recommended norms should be reviewed for later research.

Secondly, the case study is an important research method for the investigation of building environment design, which is based on the diversity of the current Chinese residential building market. The residential apartment is a typical living style of building layout design. Different prototypes of selected case studies provide a limitation of building environment factors that could form different interior microclimatic situations for physiological preferences and various non-physiological preferences. Therefore, typical prototypes of case studies would limit the research boundaries for indoor environment analysis, and are better for the validation of later field study and parametric analysis of building thermal performance research.

Thirdly, field study is a common method for building environment research of actual thermal comfort surveys (F. Nicol 1995; Ogbonna and Harris 2008; Sharma and Ali 1986; Singh et al. 2011). In this study, it is designed as two parts for quantitative and qualitative research. One part is a questionnaire survey, and the other is an on-site measurement. The questionnaire is the method for collection of subjects' personal information data and subjective environment perception. That data set aims to be used in a mathematical analysis to determine the relationship of subjective thermal preference, indoor activity schedule, personal background information and personal attitude for thermal comfort and energy saving. The questionnaire collects information; for example, the subject's activity level, clothing insulation situation, subjective perception in the real time and other parameters of the indoor thermal environment. The on-site measurement is designed as two sub-sections. One part of on-site measurement is based on the instruments recording by using an environmental thermometer and hot-wire anemometer. This is recorded in the recording sheet for the real-time environmental parameters data set, which is used for actual thermal comfort investigation. The other part of on-site measurement is based on the monitoring device for a long-term record of building indoor environment study. HOBO logger is the device chosen for this monitoring work.

Fourthly, the 'SPSS' software package is the mathematical analyzing tool used in this data analysis work. For the field study to build up a data set, it requires good software to calculate the complex mathematical relationship between building thermal environment assessment and respondents' subjective information. There is also an opportunity to discover the difference between the classic thermal comfort model and actual field study.

Fifthly, the simulation method provides a chance to effectively study the building thermal environment and examine the building thermal performance with different simulated scenarios. In this study the simulation work is based on a state-of-the art software tool, which is going to check the building energy use, comfort performance and other parametric analysis. The case study could be extended to a 3D building model with the easy-to-use OpenGL solid modeler. The simulation works by importing the field study findings and China's current recommended criterions of building design standards with data inheritance from building level, block to zone level.

Taking these methods and applications detailed above, a research framework is drawn in the next sections. This shows the reach map for this PhD research and the research methodology path.

1.6 RESEARCH FRAMEWORK

In accordance with the research questions and methodology above, a research map has been drawn for the detailed research. This framework shows a flow diagram for the next series of thesis chapters. The first step starts with the literature review in Chapter 2, and the detailed methodology of field study and case study design will be presented in Chapter 3. There are two parts to the field study survey: on-site measurement survey of objective thermal comfort sensation and a questionnaire survey of subjective thermal preference. These are presented in Chapter 4 and Chapter 5. Chapter 6 is an extension study on adaptive thermal comfort research based on the field study findings, which aims to investigate the building performance differences. Chapter 7 is the conclusion, which aims to answer to the research questions and to give technical support for further study.

The sustainability of building environment has a widely acknowledged concept that seeks to meet the needs of the present without compromising the ability of future generations to meet their own needs (formulated by the World Commission on Environment and Development in 1987) (Todorovic and Kim 2012). In other words, how to use energy in reasonable way for indoor comfortable environment maintenance is a key question in the field of building research. The building environment must concern the indoor health, comfort and sustainable development of occupants. In this research, more attention is paid to residential building environment assessment under HSCW climatic conditions in modern China. Residential building environment is a mixed mode of environmental control operated with natural ventilation (NV) control adjusted by split air conditioner (SAC) building environmental control, especially in the HSCW zone. The ASHRAE standard has proved that the comfort temperature range in NV classrooms is not suitable to the Chongqing (west part of HSCW zone) local situation (R. Yao et al. 2010). Adaptive thermal comfort theory proposes that neutral thermal sensation could be obtained by occupants' subjective operation of physiological adaptation, behavioural adaptations and psychological adaptation based on respondents' thermal preferences. This complex thermal interaction process also could be achieved in residential building with mixed mode controlling environment.

In order to extend the adaptive thermal comfort for understanding actual indoor thermal comfort sensation assessment in the HSCW zone, two typical Chinese residential building cases become involved in each research procedure, and the differences of building prototypes provide more building environment cognition for indoor thermal comfort. Indoor microclimate situations are formed by building layout designing, for example by crossing natural-ventilation for short depth building layout. The case studies in this paper concern the middle class residential building in China (usually called economically affordable housing and common commercial residential buildings mentioned in Chapter 2).

As mentioned previously, Chapters 1 and 2 present a research map for China's residential building environment in the HSCW zone and review a comprehensive literature study for China residential building development and classification, thermal comfort research about rational approach and adaptive approach, HSCW zone external environment situations, current internal thermal environment designing status in UK and China, the discomfort potential study for overheating and overcooling, and the building layout design for building performance and regional residential culture for thermal cognition. Chapter 3 describes the research method and field study procedure. Chapter 4 investigates potential problems (overheating and overcooling) in two cases in Yichang city of HSCW zone, the regional thermal sensitivity in Yichang city of the HSCW zone, the regional adaptive coefficient in Yichang city of HSCW zone, the neutral temperature and thermal comfort range in Yichang city of HSCW zone and the regional subjective thermal sensation survey. Chapter 5 further explores the occupants' subjective adaptive thermal preferences in residential building in two cases. In this section of the research a statistical analysis is presented that the anthropological factors (age, gender), socio-culture factors (education level, job style and urban living experience) and building environment layout (case A and B) difference have optional multiple regression impact for the seasonal acceptable thermal comfort limit. Moreover in this section questionnaire records also indicate regional cognition of thermal comfort and energy efficiency. Chapter 6 shows simulations that are based on adaptive thermal comfort range and neutral air temperature in HSCW zone. This section presents a parametric study for residential building performance, which include two sub-points: one is indoor thermal comfort assessment and the other one is energy consumption performance. Three different simulation scenarios of building thermal environment control (current Chinese energy efficiency scenario in the HSCW zone, current Chinese healthy housing scenario and adaptive thermal comfort scenario in the HSCW zone) were set for the simulation work and show comparative results of building performance. Moreover, subjective participation for building thermal performance research is found to have significant effect the building thermal comfort sensation and energy consumption performance that are usually influenced by objective building design. In this chapter, building shape coefficient concept has been queried and improved with the idea of building performance.

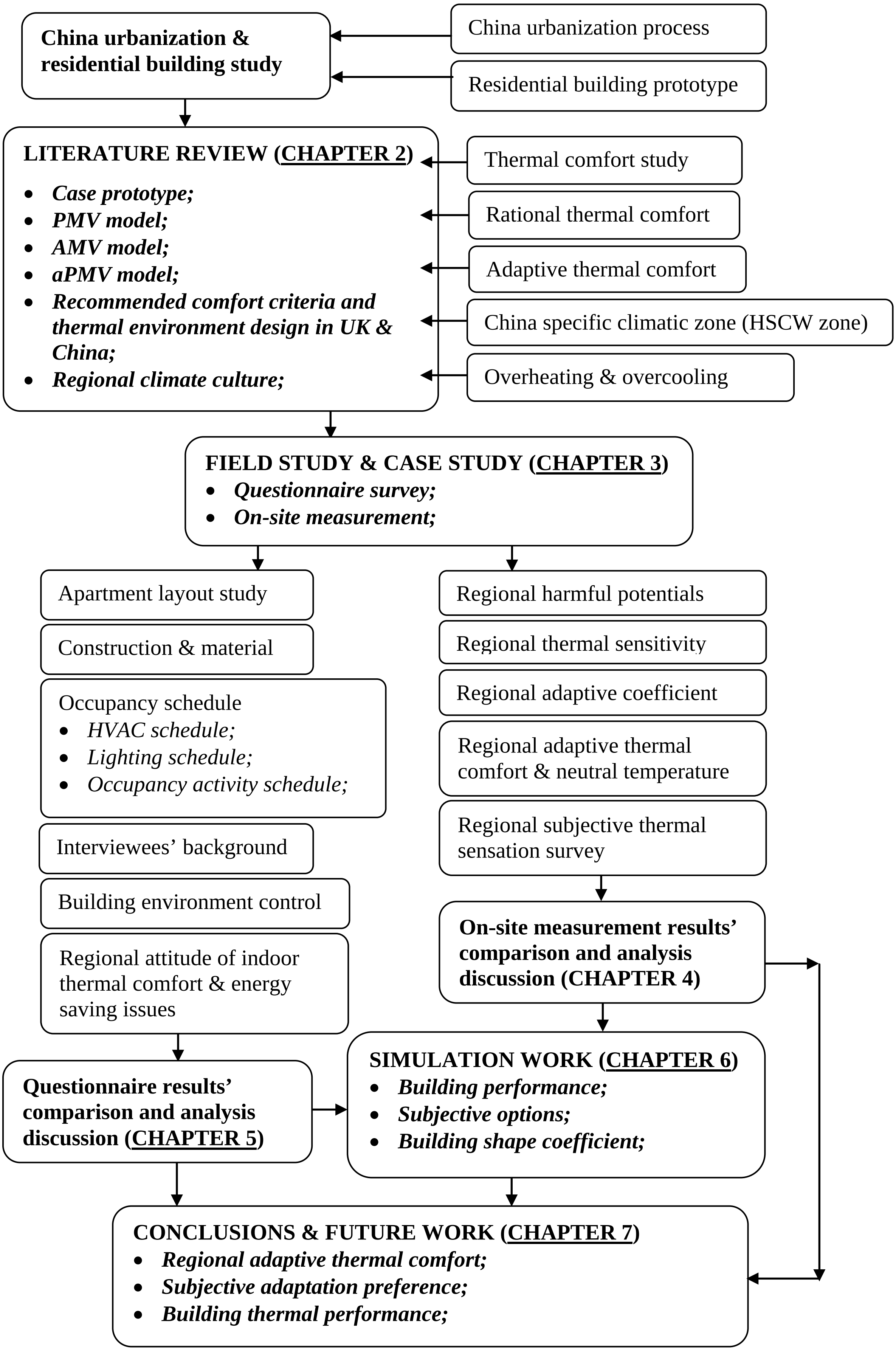
China urbanization & residential building study
China urbanization process
Residential building prototype
LITERATURE REVIEW (CHAPTER 2)
Case prototype;
PMV model;
AMV model;
aPMV model;
Recommended comfort criteria and thermal environment design in UK & China;
Regional climate culture;
Thermal comfort study
Rational thermal comfort
Adaptive thermal comfort
China specific climatic zone (HSCW zone)
Overheating & overcooling
FIELD STUDY & CASE STUDY (CHAPTER 3)
Questionnaire survey;
On-site measurement;
Apartment layout study
Construction & material
Occupancy schedule
HVAC schedule;
Lighting schedule;
Occupancy activity schedule;
Interviewees' background
Building environment control
Regional attitude of indoor thermal comfort & energy saving issues
Regional harmful potentials
Regional thermal sensitivity
Regional adaptive coefficient
Regional adaptive thermal comfort & neutral temperature
Regional subjective thermal sensation survey
On-site measurement results' comparison and analysis discussion (CHAPTER 4)
Questionnaire results' comparison and analysis discussion (CHAPTER 5)
SIMULATION WORK (CHAPTER 6)
Building performance;
Subjective options;
Building shape coefficient;
CONCLUSIONS & FUTURE WORK (CHAPTER 7)
Regional adaptive thermal comfort;
Subjective adaptation preference;
Building thermal performance;

Figure1.1 The research framework of methodology

1.7 SUMMARY

This chapter gives a comprehensive research map and brief introduction for this PhD study. It presents a clear research motivation and related research scope for the relationship between theoretical research and practical field study. It also presents the research orientation of this research and the structure of the thesis.

Table 1.1 The research structure of the thesis

THE RESEARCH STRUCTURE		
Comprehensive and theoretical study	**CHAPTER 1** INTRODUCTION	Introduce the research motivations, scopes and research questions
	CHAPTER 2 LITERATURE REVIEW	Review the historic research about China residential building development and thermal comfort approaches
Preparation of field study	**CHAPTER 3** METHODOLOGY	Introduce the method of field study and research scope
Analytical work and parametric study	**CHAPTER 4** ADAPTIVE THERMAL COMFORT RESEARCH IN CHINA HSCW ZONE	The regional adaptive thermal comfort survey outcome in HSCW zone
	CHAPTER 5 OCCUPANTS' SUBJECTIVE ADAPTATIVE PREFERENCE FOR THERMAL PERCEPTION IN RESIDENTIAL ENVIRONMENTS	The occupants' subjective impact of psychological adaptation for thermal perception
	CHAPTER 6 PARAMETRIC STUDY OF SIMULATION WORK FOR RESIDENTIAL BUILDING PERFORMANCE	The application of the adaptive thermal comfort research based on simulation work
Evaluation prospective	**CHAPTER 7** CONCLUSIONS	Conclusions and answer of research questions for further study

CHAPTER 2 LITERATURE REVIEW

2

2.1 INTRODUCTION

This chapter is a literature review for an extensive study based on the motivation presentation in Chapter 1. This chapter surveys a broad research background and presents seven points for the limitation of the research boundaries. Firstly is the research scope, where section 2.2 clearly reviews the status of Chinese residential buildings, the development of which is a unique expression of China’s urbanisation process which has propelled a booming residential building market in modern China. The Chinese residential building study also provided a clear classification for current residential building in China; the specific research object is common low-energy buildings with mid-level occupancy demand. Secondly, section 2.3 focuses on the thermal environment comfort research in the context of residential buildings, and thus a thermal comfort study is a necessary process. This includes two basic approaches to thermal comfort: one is based on lab-controlled climate chamber studies with a steady-state heat transfer approach, and the other is a summary study based on field studies with an adaptive approach to thermal environment. Thirdly, section 2.4 is a study of the ‘Hot Summer and Cold Winter’ (HSCW) zone. This section reviews thermal environment situations in the HSCW zone. Fourthly, section 2.5 is a literature study about building layout design criteria in China’s HSCW zone, in comparison with some environmental design standards in the UK. Fifthly, section 2.6 is concerned with a residential building thermal comfort study of overheating and overcooling potential in the HSCW zone. Section 2.7 focuses on building layout design of building shape coefficient combined with building energy performance. Section 2.8 concerns regional residential culture for indoor thermal comfort. These seven points provide a comprehensive literature study for this PhD research, which focuses on Chinese residential buildings. This literature review chapter presents the current regional (HSCW zone) situations in China and also draws comparison with related research into theoretical model derivations carried out all over the world.

2.2 CHINESE RESIDENTIAL BUILDING STUDY

Chinese residential building is the object focused on in this PhD research, which is a large sector of the building market that is a booming part of China’s current economic development. It represents a type of private property distributed as social welfare for different working levels in early new-China (since 1949), transformed into traded goods in the free market. Although the personal attitude and desire of residential building ownership is enthusiastic for its opportunities in addressing social problems, the urbanisation process has provided an opportunity and a challenge for a residential building revolution in both quantity and quality. In this literature study, a review of Chinese residential building development is linked with the urbanisation process of China's national periodic policy, 'Reform and Opening'.

2.2.1 CHINA URBANISATION AND RESIDENTIAL BUILDING DEVELOPMENT

In Chinese philosophy, the significance of a residential building is as a kind of family 'property ownership', and Chinese people usually view purchasing their own housing as an statement of independence for a young generation creating their own life, especially in urban areas. Owing to this aspect of Chinese social culture, the Chinese residential building market has an important place in the social development. Therefore, the Chinese urbanization process with its promotion of a socialist administration meant that the last sixty or so years since the new China was set up presented a time of great significance for Chinese residential building development. Property privatization pushed forward a booming residential building market and released the heavy burden of the civil building supplement system which had been present since the early 1970s. China's social reformation has lived up to its name 'Reform and Opening-up' in the past three decades, and the development of the building industry made huge achievements. Various social investments have been directed to the Chinese housing market following China's urbanisation.

This world-shaking social campaign in China began in 1978 (Z. Li et al. 2008). The living conditions and intentions of the occupants were gradually changed in Chinese cities, with many residential building requirements burst by the influx of social labour to urban areas. For example, in 1978, the per capita residential floor area was 6.7m^2 in urban areas (NBSC 2009), and the figure was renewed to 28m^2 (MHURD-PRC 2009) by the end of 2007, four times greater than previously. Meanwhile, the level of urbanisation increased from 10.6% in 1949 to 45.7% in 2008 (Hu et al. 2010). The record listed above indicates that the last thirty years of reform have displayed a new face on China's urbanisation system, summarised as follows.

(1970-1978)

- Chinese rural population was encouraged to leave rural areas and move for work in urban factories without fully settling.
- China's leader Deng Xiaoping's Open Door Policy—'to get rich is a glorious aim'.

(About 1980)

- Set up five special economic zones—New development policy support for the large-scale cities, modest development reform in the medium-size and active development of small cities.

(About 1984)

- 12th session of the Chinese Communist Party central committee further promotes the commercialization of pilot city-housing development for boosting the whole country's real-estate business.

(About 1988)

- People's Republic of China (PRC) Constitution allowed the usage rights of state-owned land to be transferred in a commercial way by the local government.

(About 1989)

- PRC City Planning Law was implemented for all cities in China.

(About 1992)

- The 'Southern China Tour Speech' of Deng Xiaoping pointed out 'Development as an essential criterion for building socialism with Chinese characteristics'. The policy of 'Opening the doors' was set up for all major cities' development in the inland provinces of China. There are 15 trade zones, 32 state-level economic and technological development zones, and 53 high-tech industrial development zones established at that time. The land market reforms raised the local property market rapidly.

(About 1994)

- The reform of property-related tax lead central government to share the financial benefit with local government.
- Central government set up a 'Public Accumulation Funds System' as a prologue to the upsurge within Chinese commercial residential building.

(About 1997)

- China state council relieves the restrictions on obtaining registration of permanent urban living for the non-urban population who have had a working permit and living permit for many years, and who have bought real estate in a city. They can apply for urban identity as a normal Chinese urban resident.

(About 1998)

- 15th session of the Chinese Communist Party central committee advances small towns as the object of rural economic and societal reform strategy.
- A landmark policy published by China's state council declares that real estate property is pushed out into the commercial market for all Chinese citizens, instead of the obsolete social welfare system for property distribution.
- Commercial bank loans named 'Housing Purchase Loans' are provided to general real estate occupants by the People's Bank of China, increasing capital liquidity in the real estate market and providing one way for the government to support low-income groups.

(About 1999)

- Use of a permanent residential status document named 'Hu Kou' to register citizens for official statistical assessment controlled by Chinese central government.

(About 2001)

- State Council sets up an administration system to reform the immigration registration system for handling the problems caused by the rapid urbanisation process.

(About 2002)

- Chinese national ministry of land and resources issues shares of the leasehold rights of state-owned land, aimed at stimulating commercial bids. Commercial auction sales for land exchange replace negotiation with local government.
- 16th session of the Chinese Communist Party central committee proposes a building development strategy using Chinese characteristics of development, using industrialization and urbanization to build a prosperous Chinese society.

(About 2003)

- The third plenum of the 16th session of the Chinese Communist Party central committee proposes the concept of scientific development and harmonious society. 'People first' is the core idea of sustainable development to balance the development gap between urban and rural areas.

(About 2005)

- Chinese state council uses various macro-economic control measures to stabilize residential building prices.
- The fifth plenum of the 16th session of the Chinese Communist Party central committee proposes a building target of a ‘new socialist countryside’ in rural districts (public health, education and social security, and productivity subsidy incentives for farmers).

(About 2006)

- A prescriptive suggestion was published that ‘for new residential building projects in any Chinese city at least 70% of the building layout must be for small families, with units of dwelling size under 90m^2 (968.7 square feet)’.

(About 2007)

- The Chinese government passes a property law to protect individuals’ property rights and provide more housing allowance for low-income households in cities.

To summarise, we can glance over the development track of Chinese residential building and find that it stands at a junction in the building revolution. Although there is some attempt to make policy to match the problems caused by rapid urbanisation, Chinese residential building remains central to the building industry. There are still social concerns are about financial support and quantity needs. For the next developmental decade in China, the main concerns of the residential building sector are detailed building environment controls and parametric building design. These two considerations have led Chinese residential building research to focus on building performance studies, which are useful for shaping further industrial transformation around assembly line production, detailed design, intelligent automation of building environment control and the technology of building environment-occupant interaction.

2.2.2 PROTOTYPE RESEARCH OF CHINESE HOUSING

As the reformation within the Chinese urbanisation process continues, the urban living situation has been improving from social welfare into a kind of private property as a commodity traded in the vigorous Chinese real estate market. More new residential buildings are designed and constructed to enrich the commercial real estate market for variable dwelling demand. For example, the researches of Fernandez show that nearly 80% of new buildings in China’s building stock are residential buildings (Fernandez 2007). Because of the subjective variable living demands and objective business operation targets, Chinese residential buildings have different prototypes and classifications for different levels of the market. **Error! Reference source not found.** presents two images of current Chinese residential buildings with their characteristic multiple-storey apartments, high-density clusters and various building layouts. They both represent apartment building blocks with multiple-family occupancy.

Figure 2.1 Images of high-rise Chinese apartments in urban areas (Edited by author)

The multiple-family high-rise apartment is a common type of Chinese residential building, which is a type of dwelling strategy for coping with the Chinese population pressure and the shortage of residential land that can be used in expensive urban areas. **Error! Reference source not found.** shows an example of Chinese apartments' appearance, with a designing image schema (left) and a real project photograph (right) in China's current city surroundings. They must balance the fact that more people are gradually gathering in urban areas for job opportunities and hoping for better living situations, with the demands of the residential building as a commodity in the free trading residential building market. It has been recognised that a social label stands for a kind of hierarchical production in current Chinese society. Therefore, the building size, layout design style, surrounding landscape and social environment help determine the commercial value of the units of building floor area. The Chinese government has provided an open concept outline for residential building classification. There can be a confused definition of dwelling apartments between the practical project and the policy guidance. The next part of the literature review lists the different concepts of residential building classification.

Firstly, the size of housing floor area is the most direct factor for residential building classification. **Error! Reference source not found.** lists a comparison between the data from the official policy outline and commercial guidelines respectively. The common residential buildings are classified into four main types by China’s official reports: indemnificatory housing, where the floor area is about 40-60m^2; economically affordable housing (60-80 m^2); comfortable housing (80-100 m^2); and rural housing (around 120-150 m^2). This official classification is mentioned in ‘The Outline of Eleventh Five-Year Plans on Civil Construction Issues, 2006’ (MHURD-PRC 2006). This official categorisation is based on China’s official development strategy and is different from the commercial consultancy classification, which is based on the practical experience of accumulated residential building market evaluations and is usually dominated by mainstream public media. There are five levels of residential building classification, from small size (under 60 m^2) to luxury size (over 140 m^2). The commercial classification provides more choice based on complex social classifications and experience of current living requirements, whereas the government policy outline provides a national strategy concept with categories for building industrialisation. Therefore, both of them have real significance for China’s building development; as for academic building research which connects the two elements of the government and the commercial market(Information from ‘SINA Housing Consultancy’ database.), there is no reason to become entangled with the different systems of classification.

Table 2.1 Chinese urban apartment classification by the government and commercial guidelines.

<table>
<tr><td colspan="5">Government outline (m^2)
‘The eleventh five-year planning outline of civil contracture issues, 2006’</td></tr>
<tr><td>Rural housing</td><td>Comfortable</td><td>Affordable</td><td colspan="2">Indemnificatory</td></tr>
<tr><td>120-150</td><td>80-100</td><td>60-80</td><td colspan="2">40-60</td></tr>
<tr><td colspan="5">Commercial guideline (m^2)
The data base of http://supports.house.sina.com.cn/picture/layout.php?tid=1</td></tr>
<tr><td>Luxury</td><td>Large</td><td>Middle</td><td>Common</td><td>Small</td></tr>
<tr><td>>140</td><td>120-140</td><td>90-120</td><td>60-90</td><td>< 60</td></tr>
</table>

Table 2.2 presents a review of the state criterion of health housing in China, which is the minimum floor area limit of a residential building apartment (CNERCHS-PRC 2004). That means the basic unit floor area of various dwelling designs are as follows: the ‘2 rooms plus 1 hall’ style (two-bedroom and one living room with one toilet and one kitchen) for a three-person family (parents with their only kid) is at least 51.81 m^2; the ‘2 rooms plus 2 halls’ style (independent dining space) needs 59.01 m^2; the ‘3 rooms plus 1 hall’ is 65.67 m^2;the ‘3 plus 2’ is 72.87 m^2; ‘4 plus 1’ is 77.37 m^2; and ‘4 plus 2’ is 84.57 m^2. We can see that the interval deviation is quite small, and actually it is quite different from the living requirements for the commercial residential building market.

Table 2.2The minimum area limit of residential space National Dwelling and Residential Environment Engineering Centre.

Apartment items	The minimum limit area (m^2)
Living room	16.20 (3.6mx4.5m)
Dining space	7.20 (3.0mx2.4m)
Main bedroom	13.86 (3.3mx4.2m)
Sub bedroom (double bed)	11.70 (3.0mx3.9m)
Kitchen (single side layout)	5.55 (1.5mx3.7m)
Toilet	4.50 (1.8mx2.5m)

In China, housing classification is a special social label for a general family unit, which stands for an occupant’s social background and defines a basic qualitative level of the indoor building environment. In accordance with the occupant’s social background and household income, they are settled in different social types of residential building with different building or community appearances: slum-dwelling, economically affordable housing, commercial residential building, and villa or detached housing.

1. Urban slum-village

Figure 2.2 Images of urban villages in China(resource: http://env.people.com.cn/)

Urban slum-villages are a typical kind of underclass community for impoverished and low-income groups. Commonly found in Chinese urban areas, imbalances in economic development means that some poor parts of urban areas are left without any financial supporting policy, and some urban populations take occupancy in this kind of weak building environment with poor insulation, dark indoor natural lighting, small apartment size with poor natural ventilation or cross ventilation. However, the slum-village represents a small proportion of the urban residential building sector, and, along with its timeworn appearance, it has been gradually changed by new urban construction and civil building retrofits. It is a temporary landscape in the new urbanization process.

2. Economically affordable housing (EAH)

EAH is a kind of special commercial residential building supported by the government at all levels and operated with commercial real estate investment. It is a type of indemnificatory housing policy provided for low and lower-medium income groups with a relatively cheap price. Occupants may have come from a slum-village or an urban area cleared for government constructive projects. Below is a timeline roughly presenting the series of phases of the EAH development record.

- (1991) Initial stage: policy supports for homeless group and Weak-housing group.
- (1998) Start-up period: policy supports for low-income and lower medium-income groups.
- (1999-2005) Rapid development period: policy supports for lower medium-income group.
- (2005-2010) Query period: ‘low quality and weak surrounding social environment’, housing is ‘hard to buy’ and ‘rich group is involved in EAH qualification cheating’.
- (2008) Transition period: Development of ‘low-rent housing’ and ‘price-limit housing’.

Figure 2.3 Images of economically affordable housing in China.
(resource: http://www.sx.xinhuanet.com/ztjn/2009-07/15/content_17106246.htm)

3. Commercial residential building (CRB)

Commercial housing is a market-focused operation for real estate investment, which has been a main property-purchasing approach for Chinese people's urban life in the last three decades of China's urbanisation process, with the 'reform and opening' national strategy. The market price regulation is based on the property's real economic value. Usually commercial housing is designed as a residential community with a different planning scale. It is required to be close to social service branches (school, hospital, shopping centre and even regional scenic spot). Moreover, the housing is usually designed with a middle or large size of apartment and high quality of building environment design. The marketing operation of this housing supply system plays quite an important role in releasing the housing construction and distribution burden from local government so that the local government can concentrate on the legislation of building strategies and the operation of residential landing assignments. The following **Error! Reference source not found.** and **Error! Reference source not found.** present images of commercial residential communities in Yichang, Hubei province of China. These high-rise multi-family residential buildings have a high level of construction and a detailed and well-tended surrounding landscape.

Figure 2.4 'Nan BeiTian Cheng' residential Community, Yichang, China.
(resource: http://nanbeitiancheng.soufun.com)

Figure2.5 ‘Mei An Chang Di’ residential Community, Yichang, China.
(resource: http://data.house.sina.com.cn/yc36/slide/2269504/)

4. Villa and detached housing

The luxury level of residential housing is usually located in suburban areas or large scale areas that have beautiful natural landscape. It is often designed as a low-rise dwelling villa or detached housing, or terraced townhouses. It is often purchased and occupied by the wealthy and the privileged class, which is a very small group.

Figure 2.6 Images of luxury villas and detached housing in Yichang, China.
(resource:http://yichang.house.sina.com.cn/zhuanti/shmyychz/)

To sum up all the literature on Chinese residential building development and current classification studies, we can find that the Chinese urbanization process promotes a booming alternative residential buildings market. The poor level of urban slum villages and the luxurious offering of villas or detached housing stand for a small segment of the population. Each form of housing needs national building strategies to improve and limit the scale of these groups. The other two building types are common building prototypes to deal with the increasing population problems in urban areas and the shortage of urban residential land to use. These residential building prototypes have a large purchasing space in the urban residential market. Therefore, this multi-family high-rise residential building is a main research orientation for the detailed building study. The ultimate objective is for a national sustainable building strategy in urban area construction. This is of great significance for the building environment researches scope, case selection and the survey design of the field investigation.

2.3 THERMAL COMFORT STUDY

Thermal comfort has been defined by Hensen's PhD thesis as 'a state in which there are no driving impulses to correct the environment by the behaviour' (Djongyang et al. 2010) and the official definition is 'a condition of mind that expresses satisfaction with the thermal environment', which is expressed by 'American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) in 'Standard 55-92' (ASHRAE 1992). As such, it can always be affected by personal differences in thermal preference and cognition culture, as well as other individual and social factors. The related research listed below collectively expresses the idea that thermal comfort is not just a steady physical heat transfer function, but is also a cognitive process involving and impacted by many physiological and non-physiological factors.

2.3.1 HISTORICAL STUDY OF THERMAL COMFORT

According to the conventional research of the early 1900s, the acceptable comfort zone was considered to be the range with 90% acceptability between positive and negative 2.5 centigrade either side of the neutral temperature (Szokolay 2008). Thermal comfort was considered to be influenced by environmental variables at that time. Therefore, thermal research was combined with objective environmental variables (four basic variables being temperature, radiation, relative humidity and air movement), and the target of the research was to find out the 'effective temperature' for drawing the comfort zone boundary with a single figure comfort index.

Houghten and Yagloglou proposed the first ET (‘effective temperature’) in 1927, and then related research and nomograms were devised to recognize the effect of humidity on thermal sensation. It has been widely used in the USA and in most ASHRAE publications, but also in the UK (e.g. Vernon and Warner, 1932; Bedford, 1936; Givoni, 1969; Koenigsberger et al., 1973). In 1953, Olgyay also introduced a ‘Bioclimatic chart’ presenting a comfort zone with upper limit extension by air movement and lower limit extension by radiation. In 1974, Gagge et al. created the ‘new effective temperature’ scale denoted ‘ET*’, and they devised the SET (standard effective temperature) scale in 1986, in which the superimposed SET lines could be drawn on the psychometric chart[1] devised by Szokolay in February 2001. It defined the comfort zone by the combined effect of temperature and humidity, the two most important determinants that will vary with the different weather situations for each month. It indicates that at higher humidity the temperature tolerance is reduced and on the contrary higher temperatures are acceptable at lower humidity. Below the temperature of 14℃ the SET lines coincide with the DBT and above that the slope of isotherm lines would be gradually increasing, and the coefficient of the slope is taken as the ratio of DBT and AH (absolute humidity). Therefore, the side boundaries of the thermal comfort zone would be defined as the value of lower or upper margin air temperatures (Tn ± 2.5 ℃) plus the slope coefficient effect. The warmest and coldest monthly outdoor average air temperatures would provide the neutrality temperature (Tn) for warm or cold situations respectively. The top and bottom boundaries of the thermal comfort zone are based on the humidity limit: 12 g/kg and 4 g/kg respectively. The slope coefficient equation is presented below:

DBT/AH = 0.023 × (T-14 ℃)(Equation2-1)

There is a question that requires some thought to answer, which is the concept of ‘neutrality temperature’ based on the median of respondents’ votes. There are many comfort studies for this research of correlating thermal neutrality with the prevailing climate in free running buildings. Researchers increasingly note the adaptation under continued heat transfer function. The framework of adaptive thermal sensation research is the psycho-physiological model of thermal perception.

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[1] A psychometric chart is a graph of the thermodynamic parameters of moist air at a constant pressure, often equated to an elevation relative to sea level. The ASHRAE-style psychometric chart was started by Willis Carrier in 1904. It depicts these parameters and is thus a graphical equation of state.

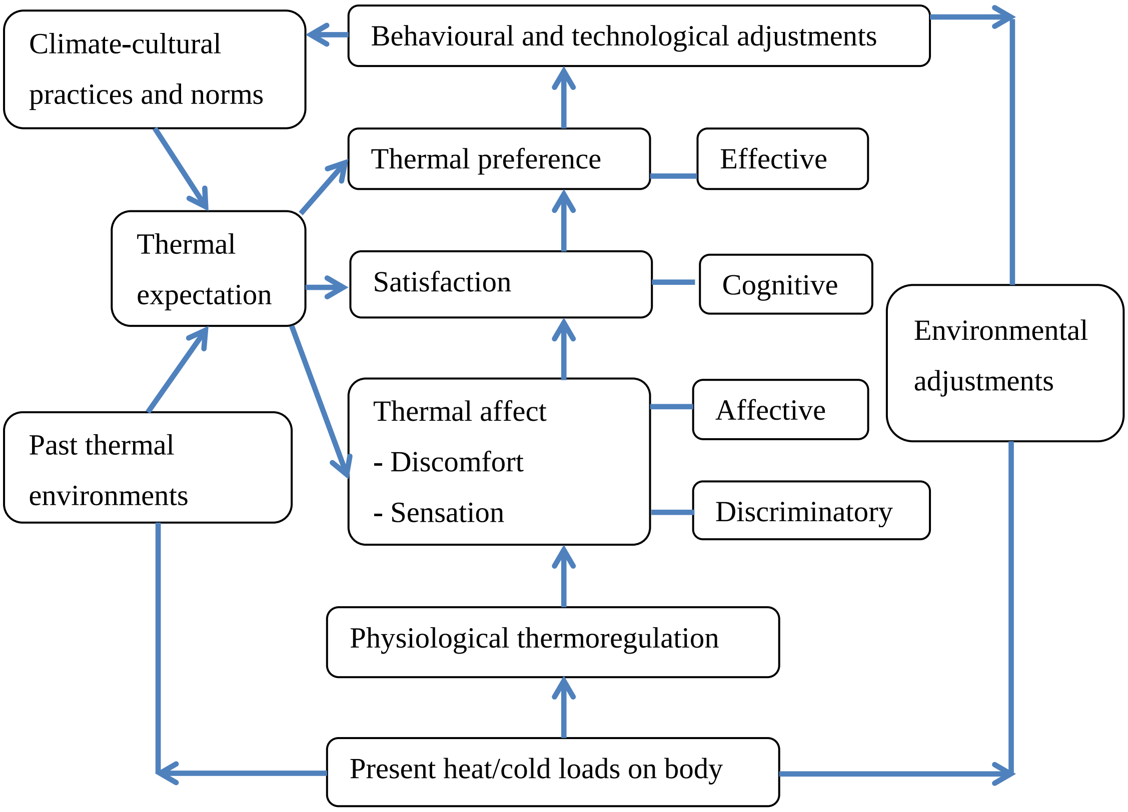

Figure 2.7 The psycho-physiological model of thermal perception edited by Auliciems (1981).

As in the framework mentioned above, it is found that the human body is not purely a passive object affected by environmental stimuli; rather, there are several subjective thermal adjustment adaptation mechanisms, which can become permanent. For example, the vasomotor adjustment is the first level of reaction against a cold (vasoconstriction) or warm (vasodilatation) environment. Long-term physiological adjustments involving cardiovascular and endocrine adjustments could become a kind of permanent physiological characteristic with the seasonal weather preference. Occupants become accustomed to the thermal environment not only physiologically but also in a way strongly linked with the psychological aspect. All of the adaptive cognitions are becoming prevailing norms. Extensive studies of neutrality temperature collected abundant field experience and many empirical formulas. In 1978, Humphreys used a large number of comfort studies with climate data in free-running buildings and proposed a neutral temperature equation. In next couple of years several related equations were extracted by other researches. These equations are listed below for study and review:

- **(1978, Humphreys)** $\mathbf{T_n = 11.9 + 0.534T_{o.av}}$ (Equation 2-2)
- **(1981, Auliciems)** $\mathbf{T_n = 17.6 + 0.31T_{o.av}}$ (Equation 2-3)

- **(1990, Griffiths) $T_n = 12.1 + 0.534T_{o.av}$** (Equation 2-4)
- **(1996, Nicol and Roaf) $T_n = 17 + 0.38T_{o.av}$** (Equation 2-5)
- **(1997, Dear et al) $T_n = 17.8 + 0.31T_{o.av}$** (Equation 2-6)

During these long-term field studies of neutral temperature analysis, thermal comfort is assumed as a complex subjective response influenced by some physical environment stimulation and some other cognitive preferences. Therefore, different equations were summed up for presentation of the relationship between neutral temperature and outside average temperature in regional weather situations. As for the study of thermal perception framework, it is found that thermal adjustment mechanisms are not only limited to the physiological mechanism, but there is also a strong relationship with psychological factors and behavioural impact. This means that prevailing environment conditions, personal social status and their cultural specifics are all important factors for the thermal sensation estimation. According to the historical derivation of thermal comfort zone research and thermoregulation perception mechanism studies, there are two different approaches for the definition of thermal comfort research. One is the heat-balance approach based on steady-state experiment studies. The other one is the adaptive approach that is based on the field study of real people's practical acceptance of indoor thermal environment, using environmental interactivity of psychological context and occupants' behaviour as the supplemental adjustment for physiological adaptation. They are a good supplement for each other: the former provides more accurate research for the heat transfer with human body in the physiological method, and the latter approach is an actual thermal sensation and dynamic acceptable thermal comfort research method to avoid underestimating or overestimating the occupants' thermal comfort in the real world.

2.3.2 THE RATIONAL THERMAL COMFORT APPROACH

The rational thermal comfort approach is a heat-balance theory based on Fanger's comfort model (P.O. Fanger 1970). The experiment-based study took place in a controlled climate chamber on 1296 young Danish students by using the steady-state heat transfer model. These participants were incorporated with the six important variables mentioned by Macpherson in 1962 for thermal performance. The four physical variables are air temperature, air velocity, relative humidity and mean radiant temperature, and the remaining two personal variables are activity level and clothing insulation. They were dressed in standardised clothing and performed standardised activities, whilst exposed to different thermal environments to record how hot or cold they felt by using the seven point ASHRAE thermal sensation scale. Much neutral thermal sensation research is based on these variables and this thermal sensation scale. Fanger's model finds that the human body employs physiological processes to maintain heat balance (sweating, shivering, regulating blood circulation and so on). Maintaining these variables for the neutral thermal sensation is the first condition for heat balance (Charles 2003). They are also widely used in field studies on thermal comfort, for example the research conducted in the hot-humid climate of China launched by Zhang et al. (Han et al. 2007). The variables are listed below:

- Air temperature;
- Mean radiant temperature;
- Relative air velocity;
- Water vapour pressure in ambient air;
- Activity level (heat production in the body);
- Thermal resistance of the clothing (clo-value).

In 1967, Fanger's research launched an investigation of the human body's physiological processes when it is close to neutral to predict the conditions where thermal comfort would occur (P.O Fanger 1967). The comfort equation was developed from the lab experiment to describe thermal comfort, and it is related to the seven-point ASHRAE thermal sensation scale. The 'Predicted Mean Vote' (PMV) index was derived from that and incorporated into the 'Predicted Percentage Dissatisfied' (PPD) index. These are important contributions of Fanger's research for the evaluation of buildings' thermal environment, widely accepted for the study design and field assessment of thermal comfort (P. O. Fanger 1982). **Error! Reference source not found.** shows the thermal sensation seven-point scale (P. O. Fanger 1982).

Table 2.3 Thermal sensation scale.

Index value	**Thermal sensation**
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral (comfort)
-1	Slightly cool
-2	Cool
-3	Cold

The heat balance model of thermal comfort is defined by the human sensation method of the PMV index. The thermoregulatory system of the human body can protect body temperature from a wide range of factors such as occupants' activity level and clothing thermal resistance. A constant thermal environment displays a constant metabolic rate of heat balance for the human body, which means that heat production is equal the heat loss and there is no significant heat storage within the body. The heat balance of the human body may be written as:

$\mathbf{H - E_d - E_{sw} - E_{re} - L = K = R + C}$ (Equation 2-7)

Where:

- H means the internal heat production of the human body;
- E_d means the heat loss by water vapour diffusion through the skin;
- E_{sw} means the heat loss by evaporation of sweat from the surface of the skin;
- E_{re} means the latent respiration heat loss;
- L means the dry respiration heat loss;
- K means the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing);
- R means the heat loss by radiation from the outer surface of the clothed body;
- C means the heat loss by convection from the outer surface of the clothed body.

This double equation express internal heat production 'H' minus the heat loss by evaporation from the skin and that by respiration. It is equal to the conduction of heat exchanged through the clothing. The outer surface heating transfer of the clothing is equal to the dissipation of the heat loss by radiation and convection. According to the oxidation processes in the human body, H equals the metabolic rate M minus the external mechanical performance. Therefore the heat balance equation could be expressed in a different way as below:

$\mathbf{\Phi m - \Phi w = \Phi rc + \Phi re + \Phi k + \Phi r + \Phi c + \Phi e + \Phi s}$(CIBSE 2006) (Equation 2-8)

Where:

- Φm is Metabolic rate (W);
- Φw is Rate of performance of external work (W);
- Φrc is Heat exchange by convection in the respiratory tract (W);
- Φre is Heat exchange by evaporation in the respiratory tract (W);
- Φk is The heat flow by conduction from the surface of the clothed body (W);
- Φr is Heat loss by radiation from the surface of the clothed body (W);
- Φc is Heat loss by convection from the surface of the clothed body (W);
- Φe is Heat loss by evaporation from skin (W);

- Φs is Body heat storage (W).

According to the equation mentioned above, if the value of **Φs** were zero in a steady condition, it does not mean that a thermal comfort is achieved. Skin temperature and sweat rates are both key factors dependent on the metabolic rate (P. O. Fanger 1982; Hensel 1981b). Steady-state experiments show that the thermal comfort of winter time is strongly related to the mean skin temperature and that warmth discomfort is caused by sweat secretion (Djongyang et al. 2010). The PMV index suggested by Fanger expresses the mean response of a large group of people, and their responses were marked using the ASHREA thermal sensation scale. The mean votes on the sensation scale stand for the overall feeling in a given climate chamber condition. The following equation displays Fanger's PMV-based idea of the imbalance between the actual heat flow from ambient environment and the heat gain from specified activity for optimum comfort:

$$\mathbf{PMV = [0.303\exp(-0.036M) + 0.028] \times L = \alpha \times L} \quad \text{(Equation2-9)}$$

The meaning of 'L' is the thermal load on the body defined as the difference between the internal body heat production and the heat loss to the ambient environment. The 'α' is the participant's sensitivity coefficient in the thermal prediction process. And the transformation of the equation is listed below:

$$\mathbf{PMV=(0.303e-0.036M+0.028)\{(M-W)-3.05\times10-3[5733-6.99(M-W)-Pa]-0.42[(M-W)-58.15]-1.7\times10-5M(5867-Pa)-0.0014M(34-T_{imt})-3.96\times10-8fcl[4(T_{cl}+273)-4(T_{mrt}+273)]-f_{cl}\times h_c(T_{cl}-T_{imt})\}} \quad \text{(Equation2-10)}$$

For the extensive thermal comfort research of PMV in the sedentary regime, the Institute for Environmental Research of the State University of Kansas simplified the equation to express the PMV in easier parameters, with the result (Orosa 2009):

$$\mathbf{PMV = aT + bP_v - c} \quad \text{(Equation2-11)}$$

The 'P_v' represents the water vapour pressure in ambient air and the 'T' represents the temperature records. The average records suggest that the comfort zone is close to a condition of 26^oC and 50% relative humidity, based on sedentary metabolic activity, with subjects dressed with normal clothing that has approximately 0.6 clothing insulation value, and with exposure to the indoor ambiences for three hours. The ASHRAE Standard 55 provides the recommended acceptable thermal comfort conditions, presented in Table 2.4.

Table 2.4 Recommended acceptable thermal comfort conditions

ASHRAE Standard 55	Operative temperature	Acceptable range
Summer	22°C	20-23°C
Winter	24.5°C	23-26°C

The PPD equation predicts the percentage of the people who will feel discomfort rather than thermal comfort. The dissatisfaction index is based on the seven-point scale of thermal sensation (-3 to +3), and the thermal comfort range is usually defined as the votes that respond with ±1 and 0 (P.O. Fanger 1972). It reveals a perfect symmetry with the thermal neutrality, and even when the PMV reaches the neutrality point (0) there still are some individual cases of dissatisfaction with the same thermal environment despite similar dress and activities. That is the personal difference and the minimum rate of dissatisfaction is 5% (Hwang et al. 2009a). Fanger's research focused on human thermal sensation in different thermal environments. The result was recognised by the 'International Standardization Organization' (ISO 1994). The PMV-PPD equation is derived from Fanger's researches (P. O. Fanger et al. 1988) and uses a computer program for calculating the value of votes. It is based on that given in BS EN ISO 7730 (BSI 1995) and the solution is based on 50% saturation. The individual thermal sensation votes will normally not be able to satisfy everyone simultaneously. The PPD value predicts the percentage of people who would be dissatisfied with the PMV value > -1 or < +1 on the human sensation scale of thermal comfort. The following equation presents the relationship between these two indexes, and **Error! Reference source not found.** shows the PMV-PPD model curve. There are three comfort levels of PPD based on the PMV admissible range presented in **Error! Reference source not found.**.

$PPD = 100 – 95 \exp [–(0.03353\ PMV4 + 0.2179\ PMV^2)]$(ISO 1994);(Equation2-12)

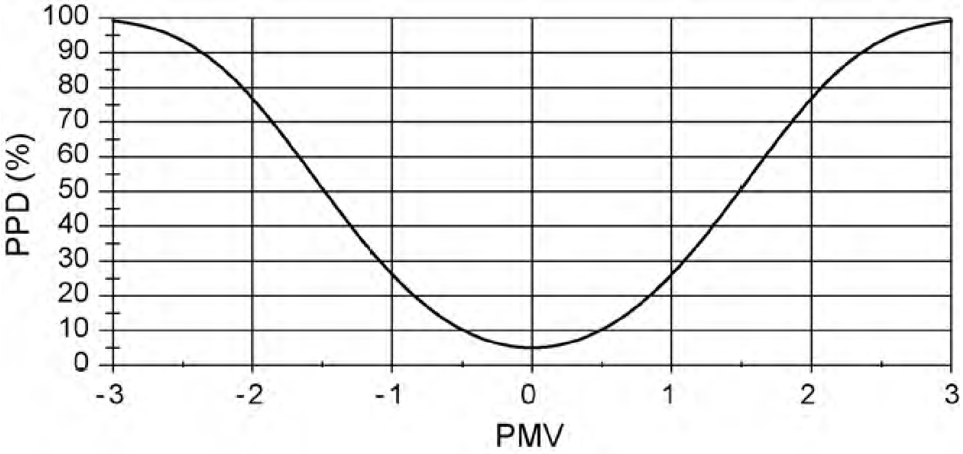

Figure 2.8 Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD).

Table 2.5 Comfort level of PPD based on the PMV

Comfort level	**PPD**	**Range of PMV**
1	<6	-0.2 < PMV < 0.2
2	<10	-0.5 < PMV < 0.5
3	<15	-0.7 < PMV < 0.7

2.3.3 THE ADAPTIVE THERMAL COMFORT APPROACH

Adaptive thermal comfort theory is based on comprehensive worldwide field studies, the fundamental assumption of which is the adaptive approach: that if the indoor thermal environment fluctuation causes discomfort, occupants will launch their reaction to restore thermal comfort in an internal or external way. The adjustments have been developed by De Dear's research in three categories: physiological adaptation, psychological adaptation and behavioural adaptation (Djongyang et al. 2010). The adaptive comfort theory was first proposed in the 1970s in response to the huge increases in oil price (G.S. Brager and de Dear 1998a). The principle of adaptive approach is that discomfort is produced by indoor climate change, and people react to restore their comfort (J.F. Nicol and Humphreys 2002b). A series of studies statistically presented a significant relationship between indoor neutral temperature and indoor air temperature, for example those developed by Humphreys (M. A. Humphreys 1978a) and Auliciems (Auliciems 1981b). Auliciems developed the a field study that was the first to propose the 'adaptive control algorithm' (ACA) in 1986, and presented an equation linking the outdoor air temperature with indoor thermal comfort temperature. This was followed by thermal survey research into free-running buildings by Humphreys, Nicol, Auliciems, de Dear, CIBSE and so on, in which a debate emerged concerning the deviation between the steady-state heat balance model of PMV index and the adaptive thermal comfort adaptation coefficient effect. The point of discussion is that the rigorous restrictions of laboratory environmental parameters are quite different from the actual buildings used in field studies; moreover, the actual thermal comfort results contain differences compared with what the PMV model predicts. According to Humphreys' field study that collected data on the thermal environment and thermal response, the indoor neutral temperature and indoor thermal comfort are influenced by the outdoor climate. Field studies in naturally ventilated (NV) buildings showed that the PMV predicts warmer thermal sensations than the occupants are actually feeling in natural ventilation buildings. In other words, the PMV usually overestimates in high temperature indoor environments and underestimates at low temperature (R. J. de Dear 1998).

In the actual building environment, the human body is not a passive recipient for ambient physical stimulation; there is cycling thermal experience of multiple feedback triggers based on psychological and behavioural adjustments. These individual adjustments have been developed by de Dear in 2004, and the summarized results suggest that there are three categories: physiological adaptation, behaviour adaptation and psychological adaptation. Afterwards, researchers increasingly paid attention to conducting field studies in addition to the usual laboratory experiments in order to register the actual comfort levels and get a clearer and more reliable interaction between building environments and occupants. They found that the static and consistent conditions of theoretical thermal environment studies do not translate into the field studies and fail to capture a real thermal experience for occupants (Schiavon and Melikov 2008). Because adaptive thermal comfort is a very complex process and the living environment is changeable and inconsistent, many comprehensive studies and trials have been launched using field studies. Some focus on thermal comfort model studies and technical researches; for example, Ogbonna and Harris applied the adaptive thermal comfort paradigm to provide empirical data (Ogbonna and Harris 2008). Pasupathy et al. study the ‘phase change material’ (PCM) selection for ‘latent heat storage’ (LHS) in building products, looking at the effect on indoor heat transfer and heating or cooling applications (Pasupathy et al. 2008). Chu and Jong presented a least enthalpy estimator (LEE) method that combines the human thermal comfort mechanism with the enthalpy theory to more precisely predict a suitable way of expressing the balance between thermal comfort and energy saving in the air conditioning system (Chu and Jong 2008). There have been comparative studies about living spaces in different times (traditional and modern) by using the adaptive approach, for example the investigation of thermal comfort for traditional and modern buildings in the Ghadames oasis of Libya (Ealiwa et al. 2001). Attention has been paid to building performance assessments and energy consumption systems. For example, Wagner et al. launched an investigation of thermal satisfaction for an office building in Germany and discovered that occupants’ thermal environment control and the perceived effect of adaptation mechanisms has a correlation with occupants’ satisfaction for the building environment assessment (Wagner et al. 2007). There has been research into the environment of hospitals; for example, Hwang et al. inspected the ASHRAE Standard comfort criteria in hospital space in Taiwan, and the investigation results revealed that patients’ physical strength and health significantly affected respondents’ thermal requirements and the thermal neutrality preference (Hwang et al. 2007). There have also been some investigations conducted in classroom space (Buratti and Ricciardi 2009; Corgnati et al. 2009; R. Yao et al. 2010). Some researchers have focused people’s sexual differences, such as Wang’s research investigating the male and female sensation difference for thermal environment and thermal comfort in Harbin city, north China. The results indicate that males have lower sensitivity to indoor temperature changes than females (the difference of neutral operative temperature is about 1.1^{o}C from males to females) (Z. Wang 2006). Some related research focused on the adaptive algorithms used to combine both static and adaptive approaches to thermal comfort (Moujalled et al. 2008), and other research corrected the mathematical accuracy of models of thermal comfort in workplace settings by using the accumulated empirical knowledge of long-term field studies (Kumar and Mahdavi 2001). Some field studies were even designed to investigate thermal comfort in downtown spaces (Zambrano et al. 2006).

As is evident by the long-time debate between the PMV index rational model and the AMV actual mean vote, in a real building environment the thermal comfort issue should influence environment design and people's personal perception. Fanger claimed there is an obvious weakness of the PMV-PPD model, and worked with Toftum to propose an "expectancy factor" (P.O. Fanger and Toftum 2002) for extending the PMV model to a free-running building in a warm climate. They thought the occupants' expectations and their estimated activities are two major factors in overestimating thermal sensation under warm conditions as calculated by PMV. The research suggests that the variations caused by the expectancy factor is roughly between 0.5 and 1.0 within three groups of high, moderate and low degrees of expectations, is 1.0 for air-conditioned buildings and is close to 0.5 in free-running buildings or a few other air-conditioned buildings. Their other hypothesis is the impact of the estimated activities. Their research is based on the data of de Dear's field study of over 3200 sets from four cities with warm climates (Bangkok, Brisbane, Athens, and Singapore). The results of each set of analysis were that the metabolic rates were reduced by 6.7% for each unit of PMV above neutral. The new PMV extension model (PMVe) could accurately predict the actual votes for non-air-conditioned buildings in warm climates. It incorporated the adaptive approach, while maintaining the classic thermal parameters of the PMV model. The low level of expectancy factor means that occupants could tolerate a higher upper acceptable temperature limit; a high metabolic rate is usually used to explain the difference. A high expectation factor usually means that occupants' actual mean votes agree well with PMV model results in HVAC systems-equipped buildings situated in cold, temperate and warm climates. Many researchers have arrived at similar findings based on their field studies. For example, the research reported by Ogbonna et al. for the field investigation in summer in sub-Saharan Africa revealed that the PMV prediction of neutrality is much higher than the actual votes (Ogbonna and Harris 2008). Corgnati et al. launched a field study in an Italian classroom and presented a hypothesis of the thermal preference that it trends as a function of the seasonal change (Corgnati et al. 2009).

The adaptive thermal comfort model is important for understanding the adaptive approach, especially the research that has been done by Yao et al. The theoretical adaptive model research provides a clear explanation of adaptive thermal comfort by applying the cybernetics concept (Black Box theory). It presents a framework for taking into account the impact of social, economical and cultural background, and the impact of previous thermal experiences for psychological and behavioural adaptations. It effectively provids a quantitative method to explain the phenomena of the deviations existing between the values of predicted mean vote (PMV) and actual mean vote (AMV) in both warm and cold indoor situations in free-running buildings. The complex process of adaptations influencing thermal comfort presents a relationship between behavioural adaptations and psychological adaptations in actual thermal sensation in the human body. The adaption mechanism is an exceedingly complicated process, and ‘Black-box’ modelling is used to describe and understand the system and predict the real thermal sensation.

The adaptive approach of thermal comfort is different from the theory of stable heat transfer. All human thermal adaptations are defined as a series of complex “Black Box” processes to provide the negative effect of “Adaptive Feedback” (R. Yao 1997). People can regulate temperature through sweat (physiological adaptation), or in the form of opening or closing a window for ventilation, taking clothing on or off, or drinking hot or cooling water (behavioural adaptation). Psychological factors specific to thermal experience in the past few days, social culture and background, education level and so on form the basis of personal thermal preference and thermal expectation.

The adaptive thermal comfort theory presents an extensive research scope for actual thermal sensation assessment. The results of field studies reveal that there is a large difference between the standard norm (ASHRAE standard 55-2010) and occupants’ real feeling for thermal sensation (Han et al. 2007). Therefore the thermal standards actually give limited help for our thermal comfort campaigns and require supplementary evidence for individual thermal cognitions and acceptability preference. For example, McIntyre’s regional preference research indicates that people who get used to being in warm climates may prefer what they call a ‘slightly cool’ environment, and people who usually stay in cold climates may prefer what they call a ‘slightly warm’ environment. Their votes are based on a three-point scale where the participants either ‘want warmer’ (+1), ‘want no change’ (0) and ‘want cooler’ (-1) (Ealiwa et al. 2001; Hensel 1981a). Wang’s research (Z. Wang 2006) confirm the same tendency suggested by McIntyre’s research.

2.4 EXTERNAL THERMAL ENVIRONMENT OF THE HSCW ZONE IN CHINA

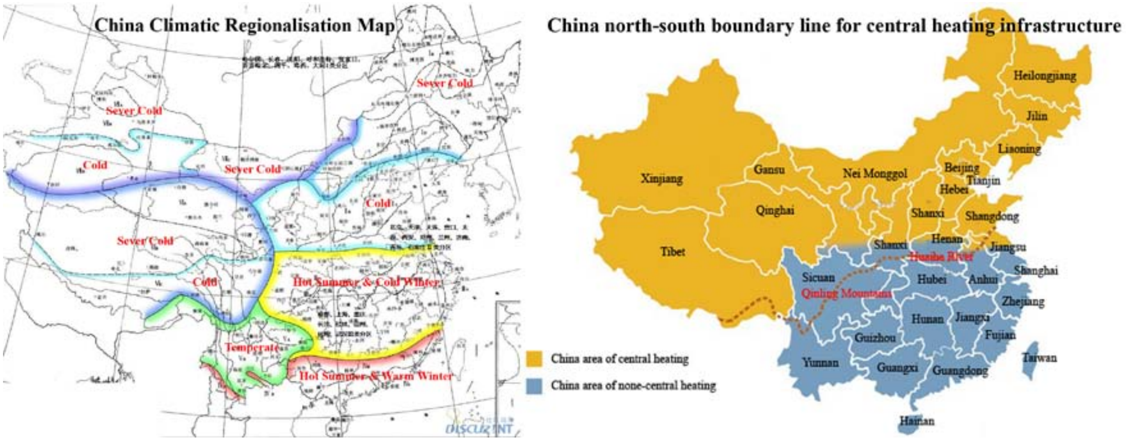

Figure 2. 9 Images of China climatic regionalization and China heating north-south boundary

Hot summer and cold winter zone is defined as one of five thermal design zones which have to deal with the problems of overheating potentials in hot summers and overcooling potentials in cold winters. In this section the relevant literature is reviewed for understanding the regional thermal environment in HSCW zone and providing background knowledge of the city that would be selected to host the field study. The regional design code and benchmark of thermal environment design present recommend thermal environment norms and design limits; for example, the building orientation setting, external shading design, inside cross-ventilation, moisture-proof design and external envelope contracture (MHURD-PRC and GAQSIQ-PRC 2003). For cold living situations the air tightness design is the key factor and there is a lack of more detailed data for thermal comfort. Yichang city is the case study location, and it has its own characteristic of climate conditions.

Taking a view of the left image in Figure 2.9, five thermal design zones are defined by thermal design codes (MHURD-PRC and GAQSIQ-PRC 1993a) to deal with the building issues under the various weather situations in China, which are named as ‘Severe Cold’ (SC), ‘Cold’ (C), ‘Moderate’ (M), ‘Hot Summer and Cold Winter’ (HSCW) and ‘Hot Summer and Warm Winter’ (HSWW) respectively. HSCW zone is located in the middle part of China on a large scale.

Firstly, the HSCW zone is composed of many districts including Hubei, Hunan, Jiangxi, Anhui, and Zhejiang provinces, Shanghai and Chongqing municipalities, the eastern part of Sichuan and Guizhou provinces, the southern part of Henan, Jiangsu, Shanxi and Gansu provinces, and the northern part of Fujian, Guangdong and Guangxi provinces (see right image in Figure 2.9). It occupies an area of 1,800,000 km^2 with 550 million people (MHURD-PRC 2010), while the GDP accounts for about 48% (B. F. Li 2004) of the whole country. The total urban residence occupied dwelling area reached 7 billion square meters (TUBEEI 2007).

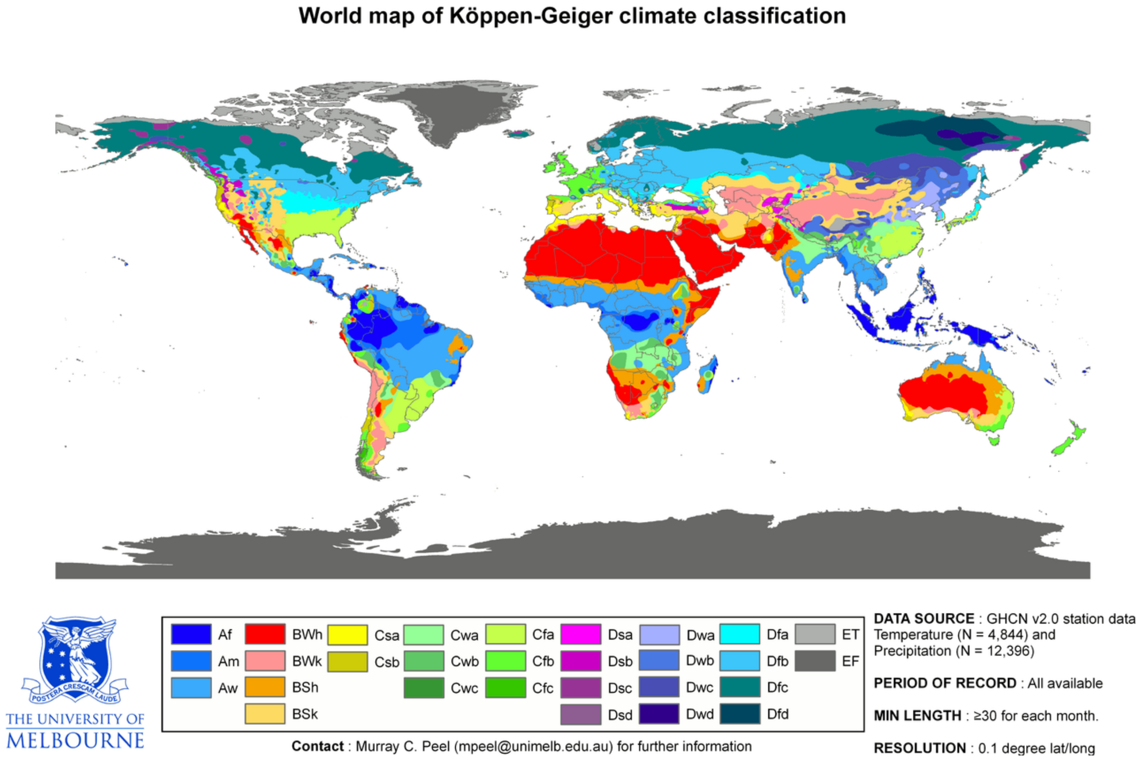

Figure 2.10 The world map of Köppen-Geiger climate classification.
(resource:http://en.wikipedia.org/wiki/File:Koppen_World_Map_(retouched_version).png)

Secondly, the weather situation of HSCW zone registers as a ‘III climatic region’ in the ‘Standard of climatic regionalization for architecture’ (MHURD-PRC and GAQSIQ-PRC 1993b). There are a total of seven climatic regions in the climatic zone classification. This region is roughly equivalent to the kind of humid subtropical climates (‘Cfa’) of group C of the Köppen-Geiger climate classification, which was first published by climatologist Wldimir Köppen in 1884 (Köppen 1936) and is the most used climate classification system, applied in worldwide climate research and academic field studies. Kottek et al. have presented an updated version of the Köppen-Geiger classification map, which is now widely used for thermal comfort surveys (Kottek et al. 2006). It is deemed that a regional thermal culture of occupants’ adaptive patterns have strong interlinks with their climate situations (M. A. Humphreys and Nicol 1998). There is a simple climate classification system developed by Atkinson based on two factors of temperature and humidity (Atkinson 1953). It has been widely accepted and distinguished as four types of zones for building design, relating to the nature of the human thermal problem. The HSCW zone is defined as warm-humid (the other three categories being cold, temperate and hot dry). Thermal sensation is aggravated by high humidity, and the diurnal temperature variation is small. The local character of this zone is extreme heat with high humidity in summer season, but wet and freezing in winter.

Thirdly, with its specific weather features, the HSCW zone is located in the central part of China, enclosed by cold, hot and moderate zones and is a transient climate zone. Based on related research in this climatic zone (Xu et al. 2013; J. Yu et al. 2011a), in summer the weather is hot with humid air and a general temperature of 25-30°C (77–86 F), with peak temperatures over 40°C (104 F). In a typical summer, an average of about 10-30 days’ temperature could be above 35°C (95F). However, the average outdoor temperature during the coldest winter month is about 0-10°C (32–50 F), and for about 20-80 days the outside average temperature is below 5°C (41F), with the lowest temperatures below 0 °C (32 F). The temperature difference between day and night is normally small. The precipitation in an average year is large, with high humidity (about 80%) and sunshine ratios relatively low from east to west due to cloud cover. In a specific climatic zone there is a basic standard to define thermal environment design requirements. Table 2.6 displays the main features (coldest/hottest monthly external temperatures) of the HSCW zone, and an auxiliary feature (days of external temperature) (MHURD-PRC and GAQSIQ-PRC 1993a). For this PhD research Yichang city is the location of the case study. It is located in the central part of China and in the middle of the HSCW zone. Table 2.7 displays a series of simple weather conditions of Yichang and some basic thermal environment data(NMIC-PRC 2009).

Table 2.6 Thermal design code for HSCW climatic zone.

Partition name	**Partition coefficient**		**Design requirement**
	Main feature	Auxiliary feature	
HSCW Zone	Coldest monthly temperature 0-10°C, Hottest monthly temperature 25-30°C	Annual days record of daily temperature ≤5° C is 0-90d; Annual days record of daily temperature ≥25° C is 40-110d;	Must defeat hot summer; heat preservation in winter time

Table 2.7 Weather data of Yichang city.

Average Value of Climate Data, Yi Chang (1971-2000)					
Month	Max°C (F)	Min°C (F)	Precipitation (mm)	Sunshine duration (hrs)	Relative Humidity (%)
Jan.	8.6 (47)	2.0 (36)	22.6	77.0	74
Feb.	10.7 (51)	3.6 (38)	30.5	78.9	72
Mar.	15.1 (59)	7.4 (45)	58.4	96.8	74
Apr.	22 (72)	13.3 (56)	36.2	133.2	74
May	26.6 (80)	17.8 (64)	129.7	154.1	74
June	29.7 (85)	21.5 (71)	148.0	153.0	77
July	32.3 (90)	24.1 (75)	216.3	186.2	80
Aug.	32.2 (90)	23.9 (75)	173.8	201.3	78
Sep.	27.8 (82)	19.8 (68)	123.0	143.6	76
Oct.	22.6 (73)	14.6 (58)	85.0	132.6	75
Nov.	16.7 (62)	9.2 (49)	46.8	113.6	74
Dec.	11.2 (52)	4.1 (39)	17.6	97.2	72
Yearly	21.3 (70)	13.4 (56)	1,138.0	1,567.6	75

Fourthly, for historical reasons (MHURD-PRC 2010), the typical dwelling apartments do not have central HVAC system or high-level insulation in the HSCW zone. With recent rapid economic development in this central part of China, energy consumption is rising, and with it comes a higher level of indoor thermal comfort requirements, with electricity being the main power for thermal comfort (TUBEEI 2007).

Fifthly, Yichang city is located in the middle of the HSCW zone, in the Hubei province of China, which has four clear seasons (spring, summer, autumn and winter) under the humid subtropical monsoon climate (MHURD-PRC and GAQSIQ-PRC 1993a). More rainfall occurs in hot summer within 24.1-28.8 ℃ in July (with extreme temperatures above 41.4 ℃), and overcast winter within 1.7-6.5 ℃ in January (with 5% probability of reaching extreme temperatures below -7 ℃). The mean outdoor relative humidity during the whole year is around 75%. Local people are accustomed to change into typical clothes by seasonal variation, and are not typically in the habit of changing their wrapping cloth for restoring thermal comfort when they enter or leave a building. Because there is no central heating or cooling system in common housing in the HSCW zone, they do not take off their heavy clothes when moving from outside to inside in the winter. Historically, there is no central heating in the HSCW zone, and energy saving typically matches the relatively low thermal comfort band to adapt to hot summer and high-humidity cold winter (16-18 ℃ in winter and 26-28 ℃ in summer) (MHURD-PRC 2010).

2.5 INTERNAL THERMAL ENVIRONMENT DESIGN IN UK AND CHINA

A housing design standard should be a good point of reference for a subjective evaluation of the balance of thermal comfort and energy efficiency. As a literature study for its application in the UK suggests, the related benchmark supplies a good sample for building a thermal environment reference. Under the impact of global warming and the energy crisis of all over the world, a UK building agency named Chartered Institution of Building Services Engineers (CIBSE) has published guidance documents. For example, some such documents are a CIBSE knowledge series of 'How to manage overheating in buildings' (CIBSE 2006; Race et al. 2010) and CIBSE Guide A - Environmental Design' (CIBSE 2006). These documents present that internal heat gains in dwelling buildings are potentially detrimental to occupant health and productivity, with high carbon emission. Thermal environment comfort is the aim of a building indoor environment design code, which involves detailed recommended criteria to be the guidelines for the building industry in UK, as researched by (Barbhuiya and Barbhuiya 2013; Ncube and Riffat 2012). 'CIBSE Guide A' provides general guidance and recommendations on comfortable temperature ranges in winter and summer for variant indoor spaces within different building types. All of the figures of operative temperature ranges use the acceptable neutrality range of predicted mean vote (PMV) between ±0.25. According to the clothing insulation and human metabolic rates indicated in section 1.3.2 of the guide (CIBSE 2006), temperature ranges would be widened by about 1°C at the each point if the values of PMV fall into the range of ±0.5, which means that a PPD of 10% is acceptable. In order to get comfortable temperatures, occupants could choose different clothing and undertake various activities, which is shown in the standard design of Tables 1.3 and 1.4 (see the Appendix section at the end of this thesis).

Table 2.8 General summer indoor comfort temperatures for non-air conditioned building of dwellings.

Building	**Operative temp. for indoor comfort in summer/°C**	**Notes**
Dwellings:		
Living areas	25	Assuming warm summer conditions in the UK
Bedrooms	23	Sleep may be impaired above 24°C

Table 2.9 Benchmark of summer peak temperatures and overheating of dwellings.

Building	Benchmark summer peak temp. /°C	Overheating criterion
Dwellings		
Living areas	28	1% annual hours over operative temp. of 28°C
Bedrooms	26	1% annual hours over operative temp. of 26°C

Table 2.8 expresses the operative indoor temperatures for indoor comfort in summer time in a free-running building (CIBSE 2006). Table 2.9 displays the design value of indoor overheating, which has a maximum peak value of 28 ºC for a living area in the benchmark and 26 ºC for a bedroom (CIBSE 2006). That is the comfortable upper limit of overheating criteria in UK. There are criteria of recommended comfort in the UK for indoor thermal environment control, and Table 2.10 shows the specific applications of the recommended comfort criteria. The detailed specification and notes are listed in the Appendix section of CIBSE Guide A.

Table 2.10 Recommended comfort criteria for specific applications

Building/ room type	Winter operative temperature range for stated activity and clothing levels			Summer operative temperature range for stated activity and clothing levels		
	Temp. (°C)	Activity (met)	Cloth (clo)	Temp. (°C)	Activity (met)	Cloth (clo)
Dwellings						
-Living	22-23	1.1	1.0	23-25	1.1	0.65
-Bedroom	17-19	0.9	2.5	23-25	0.9	1.2

Notes:
1. The summer criteria is for air-conditioned building in UK.
2. For additional data of different activities and levels of clothing see CIBSE Guide A tables 1.3 and 1.4.

In China the building thermal environment design is based on the regional (climatic zone) energy efficiency design standard (MHURD-PRC 2010) and national healthy housing technical essentials (CNERCHS-PRC 2004). They present recommended criteria for building thermal environment controls (indoor temperature range for hot summer and cold winter), but do not define the domestic overheating potential. They lack detailed investigation of adaptive thermal comfort, especially considering its regional preference in internal residential building environments. Current Chinese thermal comfort research is usually based on local legislations and design codes for energy saving strategies and the energy use of indoor thermal environment maintenance for occupants' health. There is a lack of detailed research on thermal comfort for reasonable energy use. As shown by the current research (J. Liu et al. 2012b; W. Liu et al. 2013), the important subjectivity of the participants for thermal environment adjustment and self-adaptation is increasingly realized for actual indoor thermal comfort and energy consumption. Even though people's physiological adaptation is the main factor for ambient environmental stimulates, the non-physiological factors could dictate thermal preferences that affect the physiological characteristics of the body's thermal regulation.

Firstly, there is no building environment standard for regional thermal comfort in China, and just one summary of technical essentials has been published, in 2004. The technical essentials of residential building environments (CNERCHS-PRC 2004) provides the indoor thermal parameters for occupants' health (see Table 2.11). According to the healthy housing guidelines, the environment design target is closely related to the research results published by World Health Organisation (WHO), in which the comfort range is from 17°C to 27°C within relative humidity at 40-70%. According to some correlated research from Japan, during the heating period residential space ought to be kept in the range between 18 and 22°C, and 13-20°C in non-residential space. The temperature difference between ceiling and floor should be kept below 3°C, and to 5°C between neighbouring rooms. In cooling, the internal room temperature is recommended to be in the range between 25°C to 28°C; non-residential space would better to be kept at a temperature between 26°C to 30°C. The temperature difference between indoor and outdoor should be from 5 to 7°C. Japanese indoor thermal neutrality temperature is presented at 22°C and RH 40% in winter, and 26°C and RH 50% in summer. In India, the national building code specifies a range of temperature from 21°C to 23°C for winter and a range of 23°C to 26°C in summer. These are set for air-conditioned buildings of any type in a total of five Indian climate zones (Indraganti 2010c).

Table 2.11 Indoor parameters of healthy housing.

Parameters	**Unit**	**Standard Value**	**Notes**
Temperature	°C	24-28	Cooling in summer
		18-22	Heating in winter
Relative Humidity	%	⩽70	Cooling in summer
		⩾30	Heating in winter

According to the general design code section 5.2.1 published by MHURD.PRC and GAQSIQ.PRC in 1999, the indoor thermal environment should reach a ‘*…basic level of thermal environment quality…*’ (MHURD-PRC and GAQSIQ-PRC 2003). Residential buildings located in the HSCW climatic zone ought to set up solar shading at west-facing windows. The roof and west-facing fabric envelope need insulation appliances (Heldenbrand 1974). The general descriptions of technical essentials are more confused on indoor thermal comfort, without detailed research results.

Table 2.12 (MHURD-PRC 2010) and Table 2.13 (Xiong et al. 2005) shows variant parameters for thermal design calculations in the HSCW zone. They are usually used as the academic research basis for simulation work input. In the HSCW zone, building thermal environment design is based on the energy conservation target of 50% launched in July 1996. That means that new constructions of any building type should be built with insulating materials for the reduction of the indoor maintenance energy use, saving energy compared with the amount used for building situations in 1980-1981 China. The initial target of energy conservation was a 30% reduction set in 1986, and by 2010 it basically reached the 50% energy reduction mark, with governmental policy being reviewed for a further extension to 65% saving in the new national development plan.

Tablec2.12 Thermal parameters for energy efficiency of residential buildings in HSCW zone.

Parameters	**Unit**	**Standard value**
Fresh air	m^3/(hr. person)	⩾30
Air change	Rate/h	1
Winter indoor T	°C	16-18 (18)*
Summer indoor T	°C	26-28 (26)*
Cooling energy efficiency ratio		2.3 (2.2)*
Heating energy efficiency ratio		1.9 *
Indoor lighting thermal gain	KWh	0.014
Miscellaneous thermal gain	W/m2	4.3
Note: * means the figure is a calculation value for energy consumption		

Table 2.13 The thermal parameters used in calculations of Yichang, Hubei, China.

Thermal parameters	**Value**
Heating season outdoor T (°C)	1.1
Design heating period	38 days
Heating start date	31/Dec.
Heating end date	06/Feb.
Winter vent outdoor T (°C)	1.5
Winter AC outdoor T (°C)	-0.8
Winter AC outdoor RH (%)	69
Winter outdoor mean velocity	1.4
Winter dominant wind direction	SE
Winter dominant wind velocity	2.3
Winter dominant wind frequency (%)	17
Winter outdoor atmospheric pressure (Pa)	101133
Winter percentage of sunshine (%)	25
Summer vent outdoor T (°C)	31.8
Summer AC outdoor dry-ball T (°C)	35.6
Summer AC outdoor wet-ball T (°C)	27.8
Summer AC outdoor mean daily T (°C)	31
Summer AC outdoor RH (%)	62
Summer outdoor mean velocity	1.9
Summer dominant wind direction	SE
Summer dominant wind frequency (%)	12
Summer outdoor atmospheric pressure (Pa)	98830
Yearly dominant wind direction	SE
Yearly dominant wind frequency (%)	11
Extreme max T (°C)	40.4
Extreme min T (°C)	-9.8
HDD18	1552
CDD26	148
Annual energy consumption of heating and cooling (Eh+Ec) (kW·h/m^2)	51.4

Note: Eh/Ec means annual energy consumption for heating or cooling per unit area of external wall

2.6 THE HARMFUL POTENTIAL STUDY IN RESIDENTIAL BUILDING

The indoor discomfort potential problem usually includes overheating and overcooling as two sub-branches. For ease of simulation work, a quantitative temperature limit and percentage of occupancy hours above it are investigated to establish the boundary of acceptable thermal comfort. For example, in the UK the overheating limit is reached if there are 1% of annual occupied hours that are over the operative temperature of 28°C (CIBSE 2006). In China’s HSCW zone, the description of building thermal environment control is simply limited by two indoor air temperature ranges: one is linked to energy efficient building strategy (16-18°C for winter and 26-28°C for summer) (MHURD-PRC 2010) and the other one was announced by China healthy housing, with a higher level of indoor thermal comfort (18-22°C for winter and 24-28°C for summer) (CNERCHS-PRC 2004). Thermal comfort research into building thermal environment in the HSCW zone has to deal with the impact of two extreme weather situations, causing overheating and overcooling problems in different seasons. However, there is a shortage of current housing research for this issue in the HSCW zone and especially from the viewpoint of thermal comfort (subjective adaptation) for the building environment. Some research (Ge et al. 2011; J. Yu et al. 2009a; J. Yu et al. 2011a; Zhou and Chen 2010) focused on the energy-saving technology for buildings, based on the current energy efficiency strategy for indoor environment control. Other research (Xu et al. 2013; J. Yu et al. 2013) focused on building performance for energy-saving potential. Residential buildings usually have neither free-running nor central mechanism control, which is called ‘mixed mode’ (MM) building control. There is generally more concentration on public and commercial buildings (Chow et al. 2013). Therefore the residential buildings that are located in the HSCW zone need more theoretical framework studies for indoor thermal comfort cognition and field studies in the empirical model for dynamic building environment design. Subjective thermal perception usually presents the thermal environment demand for indoor thermal comfort and determines the energy use to defeat the thermal discomfort. There are two sub-branches that are necessarily concerned with discomfort in hot summer and cold winter, which probably build up native people’s thermal experience and preferences. In this section, study of some relevant UK literature presents a good sample to get a clear idea of overheating research in the UK. Overcooling problems have also come into public notice in recent years, and people have been expressing their demand for a higher level of indoor thermal comfort. However, there is currently a lack of detailed studies.

2.6.1 OVERHEATING

With reference to studies in UK (Jenkins et al. 2009; Jenkins et al. 2012; Peacock et al. 2010; Short et al. 2012), the 'UKCP09'[2] (Jones and et al 2009) provides a wide range of possible future climate data. This is taken up by the 'Low Carbon Futures' (LCF) project for overheating analysis by applying a dynamic building simulation. The threshold limit of indoor acceptable thermal comfort is used to define when a building might be too warm or too cold, although generic recommendations are usually designed for commercial building projects (CIBSE 2006; GDES-UK 2003). The legislation of the CIBSE knowledge series presents how to manage overheating in buildings (Race et al. 2010) in a practical guide for improving indoor thermal comfort in summer time. This document is intended to assist non-expert clients, facilities managers, property owners and building users by providing the answers to some of the research questions listed below:

- What is meant by overheating in buildings and how does it relate to occupant comfort?
- How could overheating be monitored/assessed?
- What factors could contribute to overheating potential in a building environment?
- What solutions are there to the problems and what is their probable effectiveness?

Starting from an indoor thermal comfort environment, the majority of occupants feel neither too hot nor too cold within an acceptable thermal range. A low level of discomfort normally does not have any ill effects on health and only causes body reactions (sweating for warm and shivering for cold), but a high level of overheating or overcooling problems could cause potentially harmful medical conditions such as dehydration or heat exhaustion in hot environments and frostbite in cold environments (Race et al. 2010).

Thermal comfort and the overheating concept is subjective and varies from individual to individual. In the UK, CIBSE use the 'adaptive approach' in section 1.6 of CIBSE Guide A to define overheating in a building environment. As the result of adaption there is no confirmed single value to display indoor comfort or discomfort, and the comfort temperature will change with the average outdoor temperature. Therefore the definition of overheating is when the indoor temperature for any given day exceeds the 'upper limit' of the acceptable comfort temperature band and the majority of people feel uncomfortable. In overheating research, it is

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[2] UKCP09 is the fifth generation of climate change information for the UK. It is marshaled by the Met Office, which has a good understanding of how the climate system operates and is able to predict change in the future.

important to assess what the upper limit of the indoor comfort temperature is. As is well known, the occupants' changeable thermal perception is due to the psychological effect of their subjective recent thermal experiences and past thermal expectations (Auliciems 1981a; M. Humphreys 1978b). Therefore, the upper limit of acceptable indoor thermal comfort should be taken with an empirical climatic temperature calculation. The recent average outdoor temperature considered as the daily running mean outdoor temperature is better than a monthly calculation because some hot spells can suddenly happen in spring, summer and autumn (Race et al. 2010). The daily running mean outdoor temperature is defined as:

$$\boldsymbol{\theta_{rm} = (1 - \alpha_{rm})[\theta_{e(d-1)} + \alpha_{rm}\theta_{e(d-2)} + \alpha_{rm}{}^{2}\theta_{e(d-3)} \ldots]} \text{(Equation2-13)}$$

Where:

- $\boldsymbol{\theta_{rm}}$means running mean outdoor temperature for today;
- $\boldsymbol{\theta_{e(d-1)}}$means daily mean outdoor temperature for the day before that;
- $\boldsymbol{\theta_{e(d-2)}}$means daily mean outdoor temperature for the two days before that;
- $\boldsymbol{\theta_{e(d-3)}}$means daily mean outdoor temperature for the three days before that;
- $\boldsymbol{\alpha_{rm}}$means a constant between 0 and 1 that reflects how quickly the running mean responds to outdoor temperature.

Then, using the idea of infinite series for reducing the equation:

$$\boldsymbol{\theta_{rm(n)} = (1 - \alpha_{rm})\theta_{e(d-1)} + \alpha_{rm}\theta_{rm(n-1)}} \text{(Equation2-14)}$$

- $\boldsymbol{\theta_{rm(n)}}$ means running mean temperature for the day (n);
- $\boldsymbol{\theta_{rm(n-1)}}$ means running mean temperature for the day (n-1).

These running mean daily outdoor temperatures equations are applied in Europe for the office workers' survey (McCartney and F. 2002). The results of the survey present a recommended regional value constant of 0.8 in the UK (F. Nicol and Raja 1996; Race et al. 2010). This value suggests that the test week is a week with the outdoor temperature changing experience. The comfort bands allow for the relationship between outdoor running mean temperature and indoor limiting temperature, and the research presents both free-running mode (NV mode) and mixed mode (MM mode) operations. We find that the MM model building has lower sensitivity for outdoor running mean temperature changes than that of the NV mode building. The overheating phenomenon happens when the indoor temperature response strays beyond the comfort band limit. The linear relationships between indoor and outdoor temperature changes for the two different building modes are listed below.

For free-running operation:
Upper margin: $\boldsymbol{\theta_{com} = 0.33\ \theta_{rm} + 20.8}$(Equation2-15)
Lower margin: $\boldsymbol{\theta_{com} = 0.33\ \theta_{rm} + 16.8}$(Equation2-16)

For mixed operation:
Upper margin: $\boldsymbol{\theta_{com} = 0.09\ \theta_{rm} + 24.6}$(Equation2-17)
Lower margin: $\boldsymbol{\theta_{com} = 0.09\ \theta_{rm} + 20.6}$(Equation2-18)

Where $\boldsymbol{\theta_{com}}$ means the comfort temperature (°C).

Considering the reasons for overheating in general building thermal environments, it could be defined as an excessive heat invading the interior space. There are some main potential sources for overheating listed below. Moreover, the indoor thermal transfer process is a complex thermal response within various interactivities. Concerning the heat sources factors, there are both external and internal gains.

1. External heat gains:
   - Sunshine: solar radiation falling on surfaces such as walls and windows;
   - Building fabric heat transmission: When outside temperature is warmer than inside;
   - Outside warm air entering through an opening: outside warm air transfers the convection heating through the open windows, doors and external cavities on the building envelope surface.
2. Internal heat gains (Typical value to general office) (Source: CIBSE Guide A, Table 6.2):
   - Equipment (12-15w/m2);
   - Lights (8-12w/m2);
   - People (5-7w/m2).

There are three key operation strategies used to improve an indoor thermal environment and reduce indoor overheating potential: reducing heat gains, improving ventilation and occupant measures to reduce individual discomfort. A detailed description of the three strategies is drawn as a framework below.

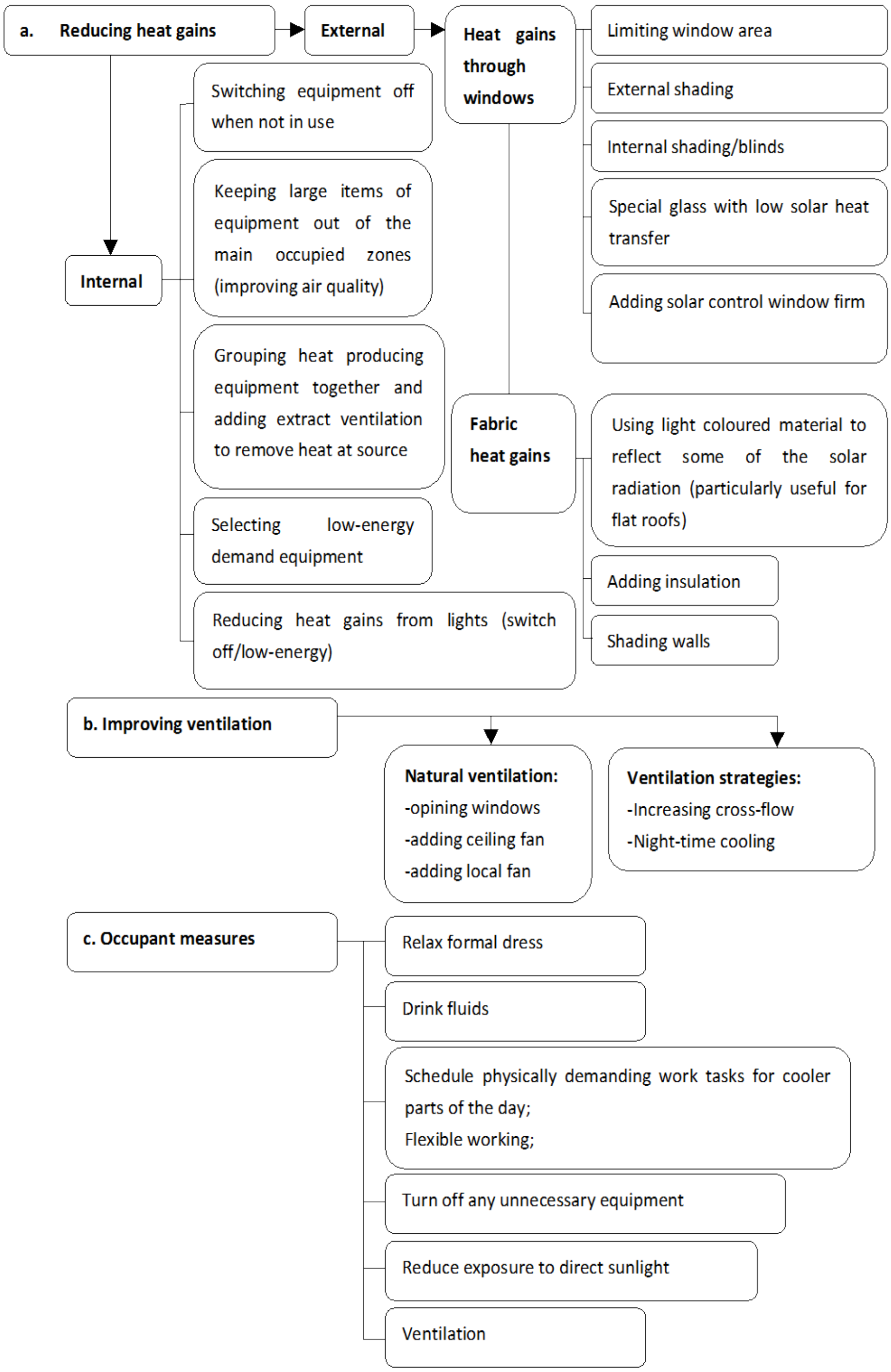


Figure 2.11 Literature review of overheating reduction approaches framework

In China, diversified weather situations mean that building design strategies have regional variations. Hot external afternoon air temperature is around 32°C or 33°C at 14:00 in the hottest month, and the maximum value could reach a peak of 40°C or more (S. Chen et al. 2010). The overheating problem is a key point both in thermal comfort and energy saving in the HSCW zone (MHURD-PRC 2010).

The overheating problem is frequently mentioned by many academic publications on building environment design; it is often thought of as the most important research topic for thermal comfort and is linked with regional energy saving issues. In the HSCW zone, the overheating criterion was defined in relation to the upper limit of 28°C and the lower limit of 16°C. There is no reference for the calculation process of temperature limit, and it is a very simple index limit without any dynamic adaptive approach.

China's overheating management method is focused on design strategies of building orientation, building fenestration and building envelope construction material. It lacks the adaptive approach that is used in UK overheating management research. The related building environment design standard cannot present a generic individual thermal experience of overheating and regional thermal preference. Therefore, there is little reason to believe that these building thermal environment control ranges could be applied for thermal comfort in actual building operations. CIBSE provides empirical equations to define the indoor temperature upper limit as the overheating threshold. The threshold limit is not a fixed single value but is a changeable value matching the fluctuation of the acceptable thermal comfort band.

2.6.2 OVERCOOLING

Overcooling is a rarely mentioned concept in the relevant research papers, but it is generally recognised that the lower margin of indoor acceptable comfort temperature is the definition and assignment for indoor overcooling. Perhaps it often escapes researchers' attention because global warming issues are in the spotlight worldwide. The HSCW zone housing designing code states that 'for historical reasons… there was no central heating like in the north part of China…' (MHURD-PRC 2010), and the overheating potential is legislated as the main prevention target. Even though the external air temperature is usually measured above the zero point, which is considerably higher than in northern parts of China, the indoor freezing thermal situation is far from the international standards of ISO 7730 (ISO 1994), ASHRAE 55 (ANSI/ASHRAE55-1994 1994) and CIBSE environment designing criteria (CIBSE 2006). For heating requirements in the HSCW zone, air-conditioning is used as a heating device in winter or other freezing times with heating requirements, as well as a cooling device in summer time. Electricity is the main source of power for heating and cooling in residential buildings.

There are some overcooling debates that have been carried out for current assessment of living environments in the HSCW zone and extending to southern parts of China without any central heating infrastructure. The partitioning method of a geographical boundary to justify a heating zone in north China and none in south China is defined by the ‘Qinling Mountains-Huaihe River’ limitation, and this partition status has been maintained sixty years. It has not satisfied the current living requirement for indoor thermal comfort caused by fast economic development. These debates have been flaring up in the face of the thermal comfort demand under intolerable cold winter conditions with a moist environment in the HSCW zone.

Although the three biggest furnace cities (Chongqing, Wuhan and Nanjing) of China are all fully located in the HSCW zone, the winter climatic situation is a terrible moist situation of unbearable freezing experiences, despite wearing heavy clothing and staying at home. Because of the indoor thermal environment situation (without continual indoor heating radiators like in the north part of China), overcooling discomfort is usually overcome by wearing heavy clothing, even in indoor spaces. Partial indoor spaces are heated by electric heaters with low power output, producing a high tolerance capacity for energy saving strategies. There is a social investigation presented on the ‘China News’ online medium into overcooling in a south China building, and measurement of indoor environment temperatures were launched in eight regional capital cities all located in the HSCW zone (China News 2013). Table 2.14 below shows the survey results of the indoor air temperature records.

Table 2.14 The social investigation of overcooling in eight regional capital cities in HSCW zone

Air Temperature	**SH**	**NJ**	**HZ**	**HF**	**NC**	**WH**	**CS**	**CQ**
Outside Space	2	3	1	0	1	3	3	5
No heating Home	6	5	7	5	4	2	8	12
Individual-heating Home	21	13	14	8	12	17	17	20
Central heating Community	N/A	23	22	19	18	14	23	N/A
Department Store	17	22	20	20	10	17	24	22
Government Office	15	20	20	16	17	13	19	16

Note: SH (Shanghai), NJ (Nanjing), HZ (Hangzhou), HF (Hefei), NC (Nanchang), WH (Wuhan), CS (Changsha), CQ (Chongqing)

According to the summaries mentioned in the above table, the average outside air temperatures are all around the range from 0°C to 5°C. If there is no heating in the home, the indoor air temperatures are close to around 10°C. Public buildings, offices and all types of heated building have warming comfort records that reach the lower limit of indoor thermal environment control for energy efficiency in the HSCW zone (16-18°C). Public buildings, governmental offices and centrally heated community buildings could even reach China's healthy housing level (18-22°C).

According to Fu's research (Xiuzhang Fu 2002b), the external critical temperature in a cooling situation for indoor heating in HSCW zone relates to the building's energy use for heating aimed at defeating the overcooling problem and determining the building's thermal performance. The level of indoor thermal comfort is higher in occident buildings, but the low level of indoor thermal comfort in China means that the external critical temperature is defined as 5-8°C (Tang and Zuo 2003). Tang's research presents a hypothetical indoor energy balance equation: that heat gathered from solar radiation and incidental indoor heat generation (from cooking, lighting, electric heat dissipation and the human body) is equal to the heat loss caused by external cooling stimuli (envelop heat transfer and infiltration heat lost though windows and doors). The results indicate that a lower external critical temperature determines a shorter heating period. Currently China's building insulation has few improvements to account for external critical temperature reduction.

A room air conditioner (RAC) is mainly used for both cooling and heating, and a low-power cooling or heating device is an auxiliary supplement for indoor thermal comfort. In the whole of China about 30 million RACs were installed in 2004, and in areas such as Shanghai the air-conditioning load accounts for 40% of the peak summer electricity power load (Lin and Rosenquist 2008). The most common air-conditioner is split-type. In fact, these devices are often inefficient in defeating indoor overcooling problems, due to the principle that heated particles rise and cool particles sink. The device hangs on the wall (lintel) above an external window, and the clear height is about 2000-2400mm. It is difficult to sink the warm air into the occupancy space, and the heating process becomes especially inefficient when an external crack or opening area causes cooling infiltration. This means that the heating period could be of long duration or require a higher set-point of supply temperature. According to practical observation, internal curtain shading is a good method of reducing the negative impact of cooling infiltration for a better heating operation. The Chinese government has legislated on the relevant technical essentials for improving air conditioner energy efficiency ratios (AQSIQ 2004). The new vision was published in 2009, and Table 2.15 shows the energy efficiency grade specifications for room air conditioners in China. Table 2.16 presents a comparison between old energy efficiency labels and the new version (2009) (Lin and Rosenquist 2008).

Table 2.15 The energy efficiency grade specifications for RAC in China

Standard Version	**Type**	**Rated Cooling Capacity (CC)W**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Old (2004)	Split	CC≤4500	3.4	3.2	3.0	2.8	2.6
		4500<CC≤7100	3.3	3.1	2.9	2.7	2.5
		7100<CC ≤ 14000	3.2	3.0	2.8	2.6	2.4
	Single		3.1	2.9	2.7	2.5	2.3
New (2010)	Split	CC≤4500	3.6	3.4	3.2		
		4500<CC≤7100	3.5	3.3	3.1		
		7100<CC ≤ 14000	3.4	3.2	3.0		
	Single		3.3	3.1	2.9		

Note: EER (Energy Efficiency Ratio) means the ratio between Cooling Capacity and Cooling Power; COP (Coefficient Of Performance) means the ratio between Heating Capacity and Heating Power.

Table 2.16 The energy efficiency specifications for energy conservation labels in China

Standard Version	**Type**	**Rated Cooling Capacity (CC)W**	**EER (W/W)**
Minimum energy efficiency ratios, first tier standard	Split	CC≤4500	2.6
		4500<CC≤7100	2.5
		7100<CC≤14000	2.4
	Single		2.3
Minimum energy efficiency ratios, 2009 standard	Split	CC≤4500	3.2
		4500<CC≤7100	3.1
		7100<CC≤14000	3.0
	Single		2.9

According to the research of Zhang et al. (Y. Zhang et al. 2013) into split air-conditioners (SACs) in hot-humid areas of China, SAC buildings are more common in south China (including the entirety of the HSCW zone) than naturally ventilated (NV) buildings or centrally air conditioned (AC) buildings. It is mixed mode, considering occupants’ adaptation preferences for both cooling and heating. For the summer time, the field investigation results indicate that, compared with NV building environments, an SAC building environment is usually kept much cooler, with more sensitivity for indoor overheating. Because their research is focused on the southern parts of China, the case study is located in the ‘Hot Summer and Warm Winter’ (HSWW) zone and the air conditioner use schedule is from May to October. There is therefore a hypothesis for the overcooling situation in the HSCW zone building environments, which is that people prefer warmer indoor environments in SAC buildings than in NV buildings.

2.7 BUILDING LAYOUT DESIGN FOR BUILDING PERFORMANCE

A residential building is usually designed as a multiple-storey high-rise building in the HSCW zone’s urban areas. As in other Asian countries with particular social-economic conditions, the building layout design aims to satisfy multiple family occupancy in one high population density block (Niu 2004; Sun 2013). The building shape is well known for a significant relationship between building energy consumption and thermal comfort (Enshen 2005). The research of Sun in 2013 concludes that residential energy conservation in China has met a barrier caused by inefficient building design (Sun 2013). According to the current Chinese building design standards, the building shape coefficient is a key determinative factor in the energy consumption audit. In China, the shape coefficient of a building is defined as the ratio of a building’s outer surface area to its inclusive volume (Cao et al. 2005; MHURD-PRC and GAQSIQ-PRC 1993a). From the viewpoint of energy saving strategies, a smaller building shape coefficient gives a potential for energy reduction of units in the building area. There are two typical building shape designs with three different shape coefficient limits. For building blocks up to three levels high, the recommended shape coefficient value is 0.55; when the building block height is in a range of between 4-7 levels the recommended shape coefficient limitation is 0.40; and when building block height is equal to or above twelve levels the coefficient limitation is 0.35 in the HSCW zone (MHURD-PRC 2010). The definition of the building shape coefficient indicates that if the volume is a constant, the value then has a dynamic relationship with the building ground floor shape, ground floor area and building height (X. Liu and Ding 2006). However, academic researchers are increasingly finding that the building shape coefficient is too rough for actual building energy performance (Lan and Huang 2013), especially because of more abundant indoor spatial designs and because the residential building market no longer necessarily accepts the ‘boring and dull’ box block design. We cannot assess the level of building energy efficiency simply by applying the shape coefficient; from the viewpoint of building performance, the energy consumption of units by indoor floor area has no significant relationship with the shape coefficient (H. Fu et al. 2010).

2.8 REGIONAL RESIDENTIAL CULTURE FOR THERMAL PERFORMANCE

Firstly, regional residential culture is typically based on ambient building environment design and construction (an objective limitation). The characteristic of the building environment is defined by regional building criteria and norms established by historical development in the HSCW zone. Chinese farming culture has a deep-rooted effect on China’s urbanisation process, which dictates that there is not much land that can be used for residential building and therefore means that there can be a shortage of resources for urban settlement exploitation. This makes high-rise multiple-family culture a basic living pattern in Chinese urban areas. The high population density of this inhabitation form could produce a special thermal cognition for the building environment. The HSCW zone has unique weather conditions that cause the construction strategy to have regional characteristics. For example, a common residential building envelope is designed as 240mm of solid clay brick, in which the thermal transfer coefficient is recommended at 2.0 W/(m^2K) without any insulation layer. Window design usually uses single glazing with a metal window frame, in which the thermal transfer coefficient is about 6.6 W/(m^2K). These design components cause poor indoor thermal comfort and also waste energy by relying on inefficient use of air conditioning and heating devices. The HSCW zone regional threshold of building energy use was presented as a series of recommended annual energy performance targets in an older version of residential building design energy efficiency standards in 2001. It provided an objective residential culture norm for the bottom line of occupants’ building environment maintenance. The energy consumption index is based on different values for ‘heating degree-day based on 18°C’ (HDD18) and ‘cooling degree-day based on 26°C’ (CDD26). Table 2.17 shows the maximum heating or cooling energy consumption in the different degree-day index values. Here we find that the monthly energy cost for 100m^2 of residential apartments in the HSCW zone could be about 110 (minimum) or 350 (maximum) CNY. This degree-day index is based on the difference between external air temperature and threshold values of building environment control limits (16 °C for heating and 26 °C for cooling).

Table 2. 17 The threshold of building energy consumption for heating and cooling

HHD18 (°C. d)	Heating load (W/ m^2)	Annual Heating (kWh/ m^2)	CDD26 (°C. d)	Cooling load (W/ m^2)	Annual Cooling (kWh/ m^2)
800	10.1	11.1	**25**	18.4	13.7
900	10.9	13.4	**50**	19.9	15.6
1000	11.7	15.6	**75**	21.3	17.4
1100	12.5	17.8	**100**	22.8	19.3
1200	13.4	20.1	**125**	24.3	21.2
1300	14.2	22.3	**150**	25.8	23
1400	15.0	24.5	**175**	27.3	24.9
1500	15.8	26.7	**200**	28.8	26.8
1600	16.6	29.0	**225**	30.3	28.6
1700	17.5	31.2	**250**	31.8	30.5
1800	18.3	33.4	**275**	33.3	32.4
1900	19.1	35.7	**300**	34.8	34.2
2000	19.9	37.9			
2100	20.7	40.1			
2200	21.6	42.4			
2300	22.4	44.6			
2400	23.2	46.8			
2500	24.0	49			

Secondly, the occupants have their own ability for building environment perception, and for accumulating personal residential culture (subjective limit) that determines the occupancy operation’s thermal environment maintenance and energy consumption. Personal residential culture has a significant relationship with personal psychological adaptation potential and behavioural adjustment habits. They supplement rather than contradict the static heat balance model (Gail S. Brager and de Dear 1998b; R. Yao et al. 2009). There is some general recognition of people’s subjective living habits in the HSCW zone that supposes that these habits have a mathematical relationship with the building environment design in the area. For example, unlike those living in the northern part of China, people usually do not take off a coat in cold winter when they enter indoor space because there is no central heating system infrastructure, and indoor environment air temperature is often closed without air conditioner operation. The HSCW zone occupants get into the habit of changing clothes by following the four different seasons (though spring and autumn may have similar clothing). Residential buildings in the HSCW zone have mixed building environment control with SAC application.

Occupants have a habit of using air-conditioners for indoor thermal comfort adjustment. Local people usually attempt to avoid a west-facing residential orientation in order to reduce overheating in hot summer, especially in the day between 13:00 and sunset. The north-south orientation of the main housing openings is considered best choice, given that a west-east angle is the most frequent wind direction for monsoons.

2.9 CONCLUSIONS

In this literature review chapter, a comprehensive research background is presented in preparation for the next series of chapters. This literature extends the research introduction with detailed studies on UK and Chinese residential buildings, thermal comfort, the external thermal environment of the HSCW zone, indoor environment design standards, overheating and overcooling potential, building layout for building performance, and the relationship between regional residential culture and thermal performance.

Firstly, the Chinese residential building study provided a chronicle for China’s 30-year urbanization process in residential building development, which is of great significance to the present research topic. Residential building classification aims to narrow down the research range to the common multiple-storey apartments of EAH and CRB.

Secondly, the thermal comfort study is a key part of the literature review that started with the whole view of historical context. There are two sub-points of the thermal comfort approach: one is the steady heat transfer method based on a laboratory climatic environment chamber, and the other is the adaptive mechanism based on field study. There is a research gap in adaptive coefficient theories to query the widely-used standard of ASHRAE 55-2010, and many field studies have found that the current thermal comfort benchmark cannot reliably describe the actual indoor thermal comfort perceptions of less sensitive occupants in naturally ventilated or free-running buildings. The subjective adaptation involved could reduce the thermal sensitivity that is at an artificially high level in the lab environment or in a perfectly controlled building environment (heating or cooling under mechanical control). There are three main factors of thermal adaptation, which are physiological, psychological and behavioural. Related research into adaptive thermal comfort suggests that adjustments in physiology and behaviour as well as psychological adaptation play a key role in reducing discomfort sensation and may be sufficient to compensate for uncomfortable physical stimuli. Psychological thermal research and awareness of subjective participation are necessary for future work on thermal control in residential building environments.

Thirdly, study of the thermal environment of the HSCW zone in China shows that it is partly a product of the region's geographic characteristics and special weather classifications.

Fourthly, internal thermal environment design represents the current thermal building environment control benchmarks in the UK and China. As well as field study data collection, this is an important parameter for building environment performance, along with simulation scenarios for thermal comfort and energy consumption.

Fifthly, this study presents a clear framework for answering the question of how to manage the overheating problem in UK. Overcooling issues in cold winter have been mentioned more in recent years in the HSCW zone, like overheating problems in hot summer. There are more heating requirements in this area. In this section, air-conditioner energy efficiency grades are also presented for more detailed examination of simulation work.

Sixthly, building layout design raises queries about the building shape coefficient in Chinese building design standards, which is defined as an energy efficiency limitation for real project audits.

Finally, regional residential culture affects a building's thermal performance, related to the interaction of objective and subjective factors. The degree-day method presents a threshold of energy consumption for heating or cooling based on external weather conditions. Although it is not a dynamic energy index calculation method with modifiable variables, it is still influenced by a regional living culture and occupants' cognition of energy usage for thermal environment.

CHAPTER 3 METHODOLOGY

3

3.1 INTRODUCTION

According to the research questions in the Introduction chapter and related research studied in the Literature Review chapter, the Methodology chapter aims to introduce field study design. It is a research procedure with multi-strategy methods widely acknowledged and used in social science research, respectively named quantitative and qualitative (Bryman 2004). The aims are to examine the ‘adaptive thermal comfort model’ in the Chinese residential building context and find out the ‘adaptive coefficient’ in the specific HSCW zone. Continuous questionnaire surveys and on-site measurements are the main approaches used for the detailed parametric study and interpretive summaries of China’s residential building environment differences. Section 3.2 presents a framework of field study in this research within three sub-points. Section 3.3 is the description of a scope of subjective and objective research. Section 3.4 introduces two case study selection and detailed layout images for further simulation work. Section 3.5 presents the respondents’ description in five points (age, gender, urban living experience, education level and job style). Section 3.6 gives a description for thermal comfort factors (clothing, activity level and sensation process). The final section 3.7 display the statistical analysis method based on computer calculation program and related statistic function application.

3.2 FRAMEWORK OF FIELD STUDY

In response to the current status of thermal comfort performance in China’s low-energy residential buildings, a field study was carried out in the ‘Hot Summer and Cold Winter’ climatic zone of China, in Yichang city of Hubei province. This was carried out in the autumn season of 2010, the seasons of summer and winter between 2011 and early in 2012. Two case studies representing two different prototypes of building layout were selected for the research and focus on questionnaire surveys and on-site measurement. Three sub-points of the field study objectives are listed in the next section.

3.2.1 REGIONAL COGNITION OF THERMAL ENVIRONMENT STUDY

Firstly, the HSCW climatic zone is a specific area defined by the Chinese thermal design code for civil building (GB50176-93) and is the zone that is defined as III climatic zone by the Chinese standard of climatic regionalization for architecture (GB50178-93). The HSCW climatic zone has a sweltering summer and moist, cold winter. For example, the average temperature of July is around 25-30^{o}C and the relative humidity is about 70-80%. In fact, the average temperature is not extremely low but it is typically 0-10°C in January. However, freezing moisture causes people to feel cold inside. According to the more detailed study in Chapter 2, the regional thermal culture study includes an important field study of an occupancy activity schedule survey. The local occupants, focusing particularly on a group of people who have steady living habits in an urban area, have relatively stable climatic expectations and preferences for the building environment (indoor environment) they are most regularly exposed to.

Secondly, the regional environmental cognition is a complex and dynamic description for the interactive relationship between the building environment and occupants. The occupants' environmental cognition survey is designed to measure two directions of thermal comfort and energy conservation. Based on the 'adaptive approach' for building thermal comfort study, the environment assessment focuses on the physiological reactions of the human body (J. Liu et al. 2012a). Related research also presents that non-physiological reactions (psychological and behavioural) have an important influence on occupants' thermal sensation and energy use for building environment comfort restoration. In this research, subjective understanding of thermal comfort and energy consumption is investigated, referring to the building design support and policy guidelines.

3.2.2 OBSERVATION OF THERMAL PERFORMANCE

Firstly, the thermal performance makes clear objective evidence for local building environment design. As the residential building environment assessment of overheating and overcooling presents the regional climate specific in the mixed model context (see section 2.6.2 and table 2.14), a hypothesis would be generated. This hypothesis is that the overcooling potential could be inevitable in cold winter under current level of residential building technical conditions and building environment control strategy, much like the overheating problem in hot summer.

Secondly, the regional thermal comfort performance studies focus on the occupants' thermal sensation in China's building contexts. The thermal sensitivity indicates the occupants' thermal responses in different building environments. Indoor air temperature is one of the most direct parameters of the thermal environment assessment. Therefore, it is supposed that the thermal response can be deduced from the relationship between the subjective model (aPMV) of ASHRAE scale votes against indoor air temperature.

Thirdly, the adaptive coefficient is the key object of thermal sensation discrepancy investigation for the regional thermal comfort range and neutral point of air temperature control. The adaptive coefficient reflects occupants' adaptive functions, which are determined by non-physiological adaptations like behavioural and psychological adaptation (see chapter 2, section 2.3.3). This is a deviation between lab-based chamber conditions and the practical real residential building environment. This accounts for an occupant's subjective participation in thermal sensation adjustment. In this research, it is supposed that the building prototypes are an important variable for this observational study.

3.2.3 PREPARATION STUDY FOR SIMULATION WORK

The field study sets up data collection for simulation work. The mixed mode of building environment control is based on the field study for occupants' thermal environment requirements and the range of acceptable air temperature. All the field study is a preparation for the simulation work input.

3.3 SCOPE OF FIELD STUDY

This field study is a long-term survey process that includes subjective questionnaire surveys and objective on-site measurement. These two main methods are based on the ASHRAE standard 55-2010 and Chinese regional low-energy building design standard. The field study is combined with occupant participation in the indoor thermal comfort survey, with the aim of obtaining the actual thermal comfort for different building prototypes in the Chinese HSCW zone.

3.3.1 SUBJECTIVE QUESTIONNAIRE SURVEY

Subjective questionnaire surveys are a common method used for social science research. In this field study there are five targets behind the questionnaire design:

- Gathering the interviewees' background information (age, gender, living experience, education level and job type) for these five groups analysis
- Gathering the activity schedule data for the average behaviour frequency of indoor activity
- Gathering the participants' cloth and metabolic rate of indoor activity;

- Gathering the data of actual personal thermal experience, overall comfort and thermal tolerance
- Gathering the on-site measurements of thermal parameters (real-time air temperature, relative humidity and indoor air velocity)

The questionnaire is designed with two sections: subjective understanding and objective measurement. Section one is designed for the investigation of general information collection. It includes four parts; respondents' background, thermal environment control, environment preference and occupancy activity schedule (air-conditioning, lighting and people) in the living room and bedroom. For this section, the questionnaire is launched in the middle month of each season within two different building prototypes. Personal preferred acceptable thermal comfort is based on the multiple-recording method, and the mean value calculation indicates the thermal experience impact on the thermal environment determination. Therefore, in this research the occupants' subjective adaptive preference research contains individual background, building prototypes' difference, seasonal impact and recent occupancy thermal experience.

Section two is the thermal sensation survey with multiple testing times for AMV sensation votes and PMV model parameters' measurements. The basic pattern is the 'Informative Appendix E-Thermal environment survey' published in ARSHARE standard 55-2010 (ASHRAE 2010). However, the reference appendix is merely informative and does not contain actual requirements in the practical building environment for conforming to the standard. The purpose of this questionnaire survey is to find an effective way to evaluate the regional occupants' thermal response to the indoor thermal environment as well as gathering thermal parameters for the PMV model calculation. For this section, the measurement is a real-time measurement synchronised with an actual thermal experience voting test. Section two is designed to focus on overheating and overcooling problems in different building prototypes, and is designed as a field study for summer and winter. The answer sheet has two parts; part one is an explanation guide of the voting scale (thermal experience, overall comfort, thermal tolerance, clothing level and activity rate) and part two is the thermal survey record. It is designed to cover two or three testing hours in a day, continuing for a week. Each testing hour is separated into two half-hour blocks with an adaptive phase.

1) Summer thermal sensation survey:
    - Case A: (22nd-27th July, 2011) (13rd-17th August, 2011) (22nd-26th August, 2011);
    - Case B: (6th-15th August, 2011)(22nd-26th August, 2011);
2) Winter thermal sensation survey:
    - Case A: (5th-22th December, 2011) (26th December-20th January, 2012);
    - Case B: (8th-21st December, 2011) (26th December-19th January, 2012);

3.3.2 OBJECTIVE ON-SITE MEASUREMENT

In this research, objective on-site measurement is made up of two parts; one part is real-time record, which synchronized subjective thermal sensation in section two of the questionnaire survey. The other part is monitoring work using data loggers (HOBO of the company onset) in two selected cases for hot summer and cold winter. The data collection of part one is based on two digital instruments that are listed below.

Figure 3. 1 The on-site measurement device

- Hot wire anemometer (RS 327-0640). Including telescopic sensor head suits air and gas flow measurement and please see the left image below (Figure 3.1 left photograph). The measurement range for air speed is 0.2-20.0 m/s with resolution of 0.1 m/s (accuracy: $\pm(5\% + 1\mathrm{d})$reading or $\pm(1\% + 1\mathrm{d})$full scale). The air temperature range is $0℃ - 50℃$ with resolution of 0.1℃ (accuracy: $\pm$0.8℃ or $\pm$1.5°F). Operating humidity is less than 80% RH;
- Environment meter (Precision GOLD N09AQ). 4 in 1 multi function environment meter (Figure 3.1 right photograph). The temperature measurement range is -20 to 750 ℃ for high level and -20 to 200 ℃ for low level, and with resolution of 0.1℃ (accuracy: $\pm(3\% + 1\mathrm{d})$). The relative humidity range is 25% to 95% RH with resolution 0.1% (accuracy: $\pm$5%RH);
- Non-contact infrared thermometer (SMART SENSOR AR862A) transfer infrared radiant energy into electrical signal of radiant temperature. The temperature measurement range is -50℃ to 900℃ with resolution of 0.1℃ or 0.1℉ (accuracy: $\pm$1.5% or $\pm$1.5℃);

In this real-time measurement process and synchronized subjective thermal sensation record, all occupancy activities of respondents are required at a distance from external window or doors, and also from indirect impact from mobile heaters or coolers. Its aim is to avoid temporary thermal stimulus which could affect subjective evaluation of thermal sensation. The measurement space height was controlled between lower than 2.0m and higher than 1.0m, which is the height range of occupants' head position when they remain standing or seated.

Indoor environment is recorded by using a calibrated method to improve accuracy and resolution of these digital measurement equipment. The sling psychrometer (whirling hygrometer) was used to verify the data in preliminary studies. Moreover, the difference between their records did not exceed 0.6 degree for the temperature and 5% for relative humidity.

For the measurement of air velocity, the telescopic sensor head of hot-wire anemometer was held near participants' head with the sensor opening direction parallel to the head surface. This is done to avoid direct influence of air draught.

For the mean radiant temperature measurement, the non-contact infrared thermometer was used in the position of respondents' sitting or standing. The mean value was recorded by calculating each measuring values of internal building surface (wall, floor and roof).

A monitoring device named 'HOBO U10-003 Temp/RH Data Logger' (MicroDAQ.com 2010) was used in on-site measurement study part two. It is designed to record months of accurate and reliable measurements. It is a two-channel temperature and relative humidity logger with 10-bit resolution. The temp/RH logger can record up to 52 readings of samples, recording as fast as one second, and has a user-replaceable battery. The data logger uses a direct USB interface for launching and data readout by the user's computer. Figure 3 shows the appearance of the monitoring device. The monitoring work and the monitoring time is listed below and presents technical indicators of monitoring devices.

1) Summer monitoring measurement in 2011: From 08:00 am of 22nd July, 2011 to 12:00 am of 2nd September, 2011 in case 1 and case 2;
2) Winter monitoring measurement at the end of 2011 and the early time of 2012: From 00:00 am of 14th November, 2011 to 05:30 pm of 12th February, 2012 both in the case 1 and case 2;

Table 3. 1 HOBO monitoring logger technical indicators

Channels	**1 temperature channel, 1 relative humidity channel**
Data Storage Capacity	52,000 10-bit Samples/Readings
Sampling Rate	1 second to 12 hours (Software Selectable)
Measurement Range	Temperature: -20° to 70°C (-4° to 158°F) RH: 25% to 95% RH
Accuracy	Temperature: ±0.4°C from 0°C to 40°C RH: ±3.5% from 25% to 85% over the range of 15°C to 45°C ±5% from 25% to 95% over the range of 5° to 55°C
Resolution	Temperature: 0.1°C at 25°C (0.2°F at 77°F) RH: 0.07% @ 25°C and 30% RH
Drift	Temperature: 0.1°C/year (0.2°F/year) RH: <1% per year typical
Response Time (Airflow: 1 m/s)	Temperature: 10 minutes, typical to 90% RH: 6 minutes, typical to 90%
Time Accuracy	Approximately ± 1 minute per month at 25°C (77°F)
Operating Range	Logging: -20° to 70°C (-4° to 158°F); 0 to 95% RH (non-condensing) Launch/Readout: 0° to 50°C (32° to 122°F), per USB specification
Battery	CR2032 Type Lithium Battery, User-Replaceable
Battery Life	1-Year (Dependent upon Sampling Rate and Environmental Conditions)
Weight	26 g (0.82 oz)
Dimensions	6.0cm x 4.7cm x 1.9cm (2.4" x 1.9" x 0.8")

Figure 3.2 HOBO data logger image

3.4 CASE STUDY

Two cases have been selected in this research with different building prototypes in Yichang city of Hubei province in the middle part of China. As the Chinese economy develops, the residential building market presents a good prospect, especially in the metropolis (Shanghai and Chongqing) area. Related building research focuses on big city development. However, the central part of China belongs to the sub-developed area in the HSCW zone, which has more urban residential requirements and space in the building market than that of a big city. Therefore, it is significant research for the residential building environment in this area and the diversity of building layouts provides various research scenarios for the thermal sensation preference survey.

According to the literature review in Chapter 2 on adaptive thermal comfort and low-energy building in China, this middle part of the HSCW zone and also the central area of China have their own unique climatic situations and thermal cognition of building environment design. For example, Yichang city is located in the HSCW climatic zone that is defined as ‘group C’ of the Köppen-Geiger climate classification (Köppen-Geiger, 1936), belonging to the humid subtropical climate - Cwa. It is different from the situations of Chongqing and Shanghai which both belong to the Cfa (‘group C’ of Köppen-Geiger climate classification). In this climate classification, ‘w’ means the driest winter month receives less than one-tenth of the precipitation of the wettest summer month, and ‘f’ means winter months get more than one tenth of the precipitation of the wettest summer month and summer months get at least 30mm per month, or more than one-third as much as the wettest winter month. This case study is therefore based on the special weather conditions in the HSCW zone.

Two cases were chosen for the field study. The first case of prototype A is B2-1-2601 located in ‘Mei An Chang Di’ (Chinese name - ‘美岸长堤‘) residential community. It is a 29-storey high-rise residential block, and the monitoring unit is on the 26th floor at the end of the building block. The other case was chosen for conducting the research on prototype B, which is B15-3-2 located in ‘Nan BeiTian Cheng’ (Chinese name - ‘南北天城’) residential community. It is on the 3rd floor of the six-storey residential block and is also at the end of the building block. In each case, two internal spaces were chosen for the questionnaire field study and monitoring work; these are the living room and bedroom.

3.4.1 CASE A

The case study of prototype A is located in ‘Mei An Chang Di’ residential community, which has a good view of the Yangtze River. This residential community is a middle-class project and the commercial prices have been increasing at about £1081.8 per square meter as at February 2012. This was exploited by Yichang ‘Jia He’ Real Estate Ltd. Corporation. They bought the land in 2007 and completed the project ready for occupancy in 2008. This project occupies 19,500m^2, and the building area is approximately 100,000m^2. The plot ratio is 5.0 and the green coverage ratio is 35%. The project was designed in the form of high-rise buildings including four residential towers and one commercial office block. There are approximately 500 tenements sharing 450 underground and surface parking units. There are four key factors to the commercial value and these are listed below:

- It is located near the Yangtze River and has excellent views of the natural landscape. There are a local historical sites and traditional buildings nearby;
- Building units are designed in capacious planes; for example, the floor area is 20% bigger than any other designs in the local residential building market;
- The external windows are mock-designed in the French window style for a good view. The balcony is designed with full-opening double-glasses;
- The shear wall structure of the frame tube is applied in these high-rise buildings and the internal thermal insulation technology is a new line of indoor thermal comfort;

Prototype A is one of a typical style designed for Chinese residential communities with long depth and a narrow facade. The case looks at a real project located on the 26th floor in a rectilinear style high-rise building block. Two tenements in each storey share one double-direction staircase and two elevators. Because of the good river view near the project, the design strategy of this building is to gather more tenements to share the beautiful landscape. Therefore, in each household the indoor rooms are combined with a Y-axis longer depth layout.

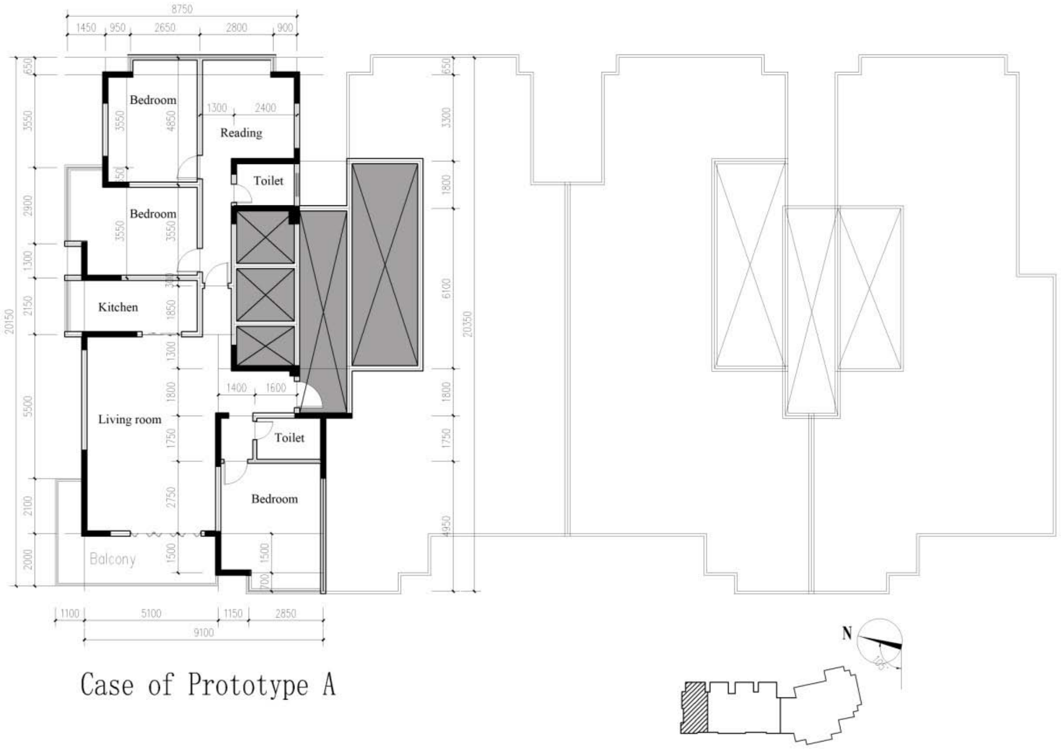


Figure 3. 3 The image of case A

3.4.2 CASE B

The case study of prototype B is located in ‘Nan Bei Tian Cheng’ residential community, which is a part of an urban redevelopment project in Yichang city of Hubei province, developed by ‘Zhejiang Nan Bei’ Real Estate Ltd. Corporation. The first phase of the project was completed in December 2004. There are 840 tenements in this residential community, and the building density is 23.5%, the plot ratio is 1.48 with a low level, and the green ratio reached about 36%. The development strategy of this project is a multi-storey building (few high-rise building blocks) with a high level of healthy residential community. Moreover, the average commercial price is about £660.1 per square meter in the 2009. Case B is one unit in a rectilinear style building block with 6-storey design in the first-phase project. It is located on the third floor.

Prototype B is a typical residential design with the inner spaces following a horizontal layout. All spaces are organised with the X-axis corridor, and the unit plane is a relatively short depth with a wide facade. It is a square building layout with more of an external opening ratio at the main building orientation for sunlight and more natural ventilation. This type of building prototype is usually designed for multi-storey residential buildings, not for high-rise buildings.

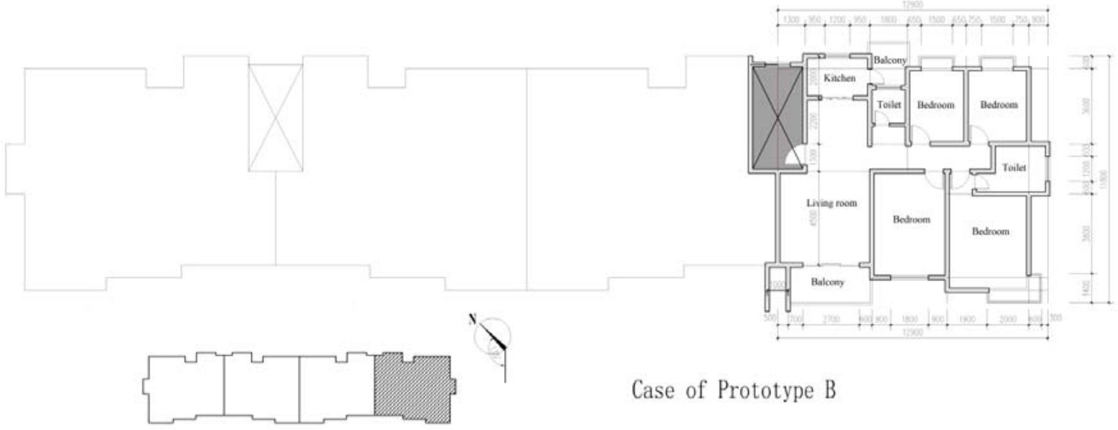


Figure 3.4 The image of case B

3.5 INTERVIEWEE

The interviewee selection is based on the five-point category method presented below, which aims to let the subjective survey have its typical significance. Each interviewee lives in the two case project communities, ten in each. They could finish section one of the questionnaire in approximately half an hour, and then proceed to participate in section two over a number of testing days.

3.5.1 AGE

All the interviewees are selected from the age range of between 15-64 years old, which is the mid-group of the overall population age composition; this group accounts for more than 70% total population nationally or regionally. Table 3.2 displays three levels (national, provincial and local city) of population age composition (NBSC 2009).

Table 3.2 The composition of Yichang, Hubei province and the national population in China

Age Composition	**0-14 years**	**15-64 years**	**65+ years**	**Total**
National total (M)	222.46	998.43	118.83	1339.72
6th National Population Census	16.60%	74.53%	8.87%	100%
Hubei province (M)	7.96	44.07	5.20	57.24
6th National Population Census	13.91%	77%	9.09%	100%
Yichang city (M)	0.756	3.03977	0.35354	4.14931
5th National Population Census	18.22%	73.26%	8.52%	100%

According to psychological research, adulthood is usually defined as being from 24 or 25 to 60 years old, and during this term human beings typically maintain steadier characteristics than in childhood, teenage-years, adolescence or old age. The sensation of the human body and psychological realisation are more clear and mature in this age range. 40-years old is the mark for the two groups comparison. There are two main reasons for this grouping demarcation. One is that the 40-year old is the medium value of China's national age composition for the group of 15-64 years old, and the other is based on the common psychological division of adulthood into two phases – the former stage (24/25-40 years old) and the later period (40-60 years old).

3.5.2 GENDER

Individual differences relating to thermal comfort are usually well recognised, but gender difference is usually underestimated (along with clothing difference) and considered to be only a minor factor (P.O. Fanger 1970; K.C. Parsons 2003). For example, Fanger found no great difference in preferred temperature between genders in climate chamber studies, only stating that a female is more sensitive to a deviation in environment optimum. There is a series of related research studies focusing on gender differences that produced markedly difference results from laboratory studies (Beshir and Ramsey 1981; Griefahn and Kunemund 2001; K. C. Parsons 2002), field studies in offices (Muzi et al. 1998; Nakano et al. 2002), an environment with noise in climate chamber (Pellerin and Candas 2003) and so on. It was found that females are more sensitive than males in both high and low temperatures, and a female group could feel cooler than a male group in cool conditions. In Japan, research presents a female group as feeling unusual coldness in an environment in which most people feel comfortable (Nagashima et al. 2002). For the HSCW zone in China, residential building has its special building environment climate and gender differences should be tested in field studies. This is the first time a gender-conscious study in residential building environments located in the HSCW zone has been launched.

3.5.3 URBAN AREA LIVING EXPERIENCE

In this field study, living experience is designed as a parameter of the questionnaire survey. For modern China's citizens, their living experience is not exclusively in the urban area. Older adults in particular have spent a considerable part of their lives in rural areas of China. Therefore, in this field study urban area living experience is involved in the questionnaire for seasonal thermal comfort preference. The respondents were divided into two groups; one group of those who have spent over 50% of their lifetime in urban areas and another group with less than half their lifetime. Living habits and life memories could affect thermal expectation and preferences.

3.5.4 EDUCATION LEVEL

Educational background usually determines the level of social effects for the interviewee, and if education levels have a strong relationship with thermal comfort realisation it would be included as a grouping in the questionnaire survey analysis. There are three levels of education: low level, which is the national compulsory education (middle school, high school and that which is lower than a Bachelor’s degree); middle level, which is a basic professional education (University education level and that which equals a Bachelor and Master degree); and high level, which is a researching professional education, for example PhD researchers or senior professionals. These categories are similar to those used in Yamtraipat’s research into the three levels of education classification, namely post graduate (higher than Bachelor’s degree), graduate (Bachelor’s degree) and scholar (lower than Bachelor’s degree) (Yamtraipat et al. 2005). In this PhD research, the education level classification dynamically affects national education status in modern China.

3.5.5 JOB STYLE

A job style typically decides a person’s daily behavioural habits and thinking style. Three types of job are delineated in the questionnaire, namely manual jobs, mental jobs and mixed jobs. Job type is a key factor for individual differences of psychological adaptation, and this study suggests a hypothetical link between thermal comfort sensation and job preference. It is defined as one of several social situation variables (job, education, income, family type and size) that are significant for the correlation of thermal comfort variables in Sugini’s 2007 ‘Thermo-Adaptive-Psychological’ thermal comfort concept (Sugini 2012).

3.6 THERMAL COMFORT FACTORS

Thermal comfort is a kind of subjective assessment for ambient building environments, which expresses satisfaction with environmental variables. Basically, there are thermal comfort factors that are related to the adaptation process in physiological thermoregulation, influenced by Psychological thermoregulation (behavioural adaptation is well known for both physiological and psychological processes). According to the rational approach to thermal comfort study, a series of statistical data collected to describe thermal comfort is composed of six primary factors listed below. They are divided into two groups: group one includes four climate variables and group two includes two personal variables. This statistical data is prepared for the rational approach of the PMV model for steady-state experiments in a climate chamber.

1. Climate variables:

- Indoor air temperature;
- Radiant temperature;
- Air speed;
- Humidity.

2. Personal variables:

- Clothing insulation value;
- Metabolic rate of activity level.

3.6.1 CLOTHING INSULATION VALUE

In this research, the clothing insulation value is directly based on the ASHRAE Standard 55-2010 reference. There are three methods involved in the standard, based on tables B1 and B2; table B1 shows the clothing insulation values for typical clothing ensembles and table B2 shows garment insulation. In the thermal sensation of PMV calculation processing, 'method 3' was used in the clothing insulation element of the questionnaire survey. The insulation of the ensemble is estimated as the sum of the individual values listed in Table B2, which is attached in the appendix section in this thesis. The estimated insulation of an example ensemble consisting of overalls worn with a flannel shirt, T-shirt, briefs, boots, and calf-length socks is given below:

$I_{cl} = 0.30 + 0.34 + -0.08 + 0.04 + 0.10 + 0.03 = 0.89\text{clo}$(3-1) (ASHRAE 2010)

For the real-time measurements of a PMV calculation, the clothing insulation values could be completely at variance in section two of the questionnaire. Table 3.3 presents seasonal samples for four seasonal clothing types; for instance the numerical insulation value of spring season clothing was designed at 0.63clo, and 0.45clo in summer time. In the autumn season the clothing insulation is designed at 0.89clo and in wintertime the clothing value is about 1.28 clo.

Table 3.3 Four seasonal clothing ensemble samples

Spring	**Clo**	**Summer**	**Clo**	**Autumn**	**Clo**	**Winter**	**Clo**
T-shirt	0.08	**T-shirt**	0.08	**T-shirt**	0.08	**Bra**	0.01
Ankle socks	0.02	**Ankle socks**	0.02	**Ankle socks**	0.02	**Panties**	0.03
Trousers (thin)	0.24	**Trousers (thin)**	0.15	**Trousers (thin)**	0.24	**Long underwear top**	0.20
Shoes	0.02	**Shoes**	0.02	**Shoes**	0.02	**Long underwear bottoms**	0.15
Skirt (thick)	0.23	**Skirt (thin)**	0.14	**Skirt (thick)**	0.23	**Shoes**	0.02
Men’s briefs	0.04	**Men’s briefs**	0.04	**Men’s briefs**	0.04	**Ankle-length athletic socks**	0.02
-	-	-	-	-	-	**Straight trousers (thick)**	0.24
-	-	-	-	-	-	**Long sleeve sweaters (thin)**	0.25
-	-	-	-	-	-	**Single breasted jacket (thick)**	0.36
Total	0.63	**Total**	0.45	**Total**	0.63	**Total**	1.28

3.6.2 METABOLIC RATE OF OCCUPANT ACTIVITY LEVEL

In this study, the metabolic rate is referred to a normative appendix of activity levels presented in the ASHRAE Standard 55-2010. These activity level values represent the typical metabolic rates per unit of skin surface for an average adult who has average skin surface area of 1.8 m^2, or 19.6 ft^2 within continuous behaviour status. According to the age group selection, the guideline is a good reference to make sense of activity levels for interviewees, and they could use their judgment to match the activities by comparison with the values in the table.

According to related research into the metabolic rates linked with the PMV method in the study of thermal comfort, if the value increases above 1.0 met the evaporation of sweat will become an increasingly key factor for thermal comfort. However, the PMV method does not fully account for this factor. Therefore the ASHRAE standard should not be applied to conditions where the average metabolic rate is above 2.0 met.

3.6.3 THERMAL SENSATION PROCESSING

The subjective thermal sensation votes are usually based on the seven-point thermal sensation scale recommended by ASHRAE standard 55-2010. The seven-point scale of thermal sensation is defined as follows: +3 (hot), +2 warm, +1 (slightly warm), 0 (neutral point), -1 (slightly cool), -2 (cool) and -3 (cold). It is based on the heat balance principles combining the six thermal comfort factors and the PPD index related to the PMV. The recommended thermal comfort range mentioned in the ASHRAE standard 55-2010 is different than that in practical experience in China. The general comfort range of US standard (ASHRARE Standard 55-2004) (ASHRAE 2010) and UK environmental design code (CIBSE Guide A-2006 Environment Design) is between ±0.5 (CIBSE 2006), however in practice the range is usually between ±1. A thermal sensation survey does not simply focus on the actual PMV index (aPMV), which is a practical voting result. It also extends to three processes, altering the aPMV to reflect thermal experience generating thermal tolerance estimations directly, with the overall comfort decision then being accumulated periodically and forming a preference for the next thermal experience.

The PMV mode calculation is based on the computer program for calculation of PMV-PPD that is mentioned in ASHRARE Standard 55-2004 ‘Normative Appendix D’. It is retrieved from Annex D of ISO 7730. However, the computer mode could only be applied to the cases in which the participants’ activity level is between 1.0 met and 2.0 met of the average metabolic rates, and the clothing insulation value is 1.5clo or less. The PMV model is also limited to air speeds not greater than 0.20 m/s (40 fpm). If the indoor thermal situations are greater than the limited ranges mentioned above, the upper limit of the thermal comfort zone may be altered to account for the increase (ASHRAE 2010).

3.7 STATISTICAL ANALYSIS

Statistical analysis is based on the statistical package for social science (SPSS), which includes both questionnaire survey data and on-site measurements. The descriptive statistics method presents the proportion of interviewees’ response by group, from which a summary of the record parameters and voting tendency of people’s thermal sensation can be deduced. Data analysis based on SPSS software’s independent sample testing is used for two groups significant difference variables, and a one-way ANOVA test is used for three groups significant difference variables. The linear regression analysis method is used for single or multiple independent variables’ correlation studies for thermal comfort variations in the HSCW zone. For multiple independent variables, the ‘enter’ method is used to track the independent variables that have a high-level correlation value with the acceptable thermal comfort range limit. The statistical-mathematic method aims to summarise thermal sensitivity, adaptive coefficients, regional thermal comfort ranges and the occupants' subjective adaptation preferences for thermal perception in residential building environments located in China's HSCW zone.

3.8 CHAPTER SUMMARY

This chapter aims to clearly present the research methods used in this study, with their framework and scopes. The field study is composed of a questionnaire survey and on-site measurements in two selected cases with different building layout prototypes. For the interviewees, age, gender, living experience, education level and job style are the parameters for the subjective background information used in determining thermal preference variables. They are based on related research and some have not been employed in previous studies. For the thermal comfort methodology, the references methods are based on international standards and normative data. This methodology is typically used in thermal comfort research across the world for field study of building thermal environment evaluation research under different climatic situations. It is used in this research alongside a subjective information survey, making this methodology more effective in investigating the regional occupants' thermal environment cognition (thermal comfort sensitivity, thermal preference and related psychological impacts or suggestions).

CHAPTER 4 ADAPTIVE THERMAL COMFORT RESEARCH IN CHINA HSCW ZONE

4

4.1 INTRODUCTION

In this field study the adaptive thermal comfort theory is used for an investigation of the adaptive coefficient and regional thermal comfort in a residential building in a ‘Hot Summer and Cold Winter’ (HSCW) zone of a central region of China. This research was undertaken using two different prototypes of selected cases which are controlled by mixed modes of temperature regulation, with natural air ventilation. The field study was based on data collected from a subjective questionnaire survey and an objective on-site measurement. The aims of the study are to investigate the regional thermal environment status of overheating or overcooling potential, to gather comparable results of two prototypes to use in a case study for thermal response sensitivity, and to calculate the adaptive coefficient and thermal comfort range for a residential building in a HSCW zone. The section 4.2 gives a detailed study of adaptive thermal comfort in China and other countries. The section 4.3 presents the method of this chapter research. The section 4.4 introduces the summaries of field study. Section 4.5 presents the overheating and overcooling potentials’ research in HSCW zone. Section 4.6 focuses on the regional thermal sensitivity study based on field study data analysis for regional adaptive coefficient and regional thermal comfort range in two different residential units. Section 4.7 gives a detailed study of regional subjective thermal sensation research about respondents’ thermal experience, overall comfort and thermal tolerance capability.

4.2 THE DETAILED ADAPTIVE RESEARCH

With more than three decades of ‘reform and opening’ development (Gu et al. 2012), the China urbanisation process has stimulated the rural area into growing larger; similar to the size of a village settlement. The population is growing and gathering together due to the construction of new residential buildings. One important research point of the building environment is high quality thermal environment design. What is a reasonable process to consider for indoor environment design? The key idea is ‘people first’ and subjective participation. As the relevant statistics show, people usually spend 80% of their lifetime undertaking indoor activities (R. Zhao et al. 2004), and in industrialised countries the percentage could be over 90% (Skoog et al. 2005). Poor levels of indoor comfort influence occupants’ productivity and health (S. Atthajariyakul and Leephakpreeda 2004; Kosonen and Tan 2004). Moreover, the Chinese building sector are responsible for around 27.5% of the total national energy consumption and in the next 20 years the energy use percentage is predicted to rise to 40% (Chow et al. 2013). The investigation of actual thermal comfort is a sustainable option for China's green building developments to consider. It is also a successful way to express the national development strategy of future 'green building technology' planning for China's 12th 'Five-Year Plan'.

The adaptive thermal comfort theory is based on a comprehensive worldwide field study, the fundamental assumption of which is that if the indoor thermal environment fluctuation causes discomfort, occupants will launch their reaction against this discomfort to restore the thermal conditions. This could take place in an inner or exterior way. The adaptive comfort theory was first proposed in the 1970s in response to the huge increases in oil price (G.S. Brager and de Dear 1998a). The principle of the adaptive approach is that discomfort is produced by indoor climate change, and people react to restore their comfort (J.F. Nicol and Humphreys 2002b). According to the field study of the thermal response, it is found that the outdoor climate has a strong relationship with indoor air temperature. This theory was developed by Humphreys (M. A. Humphreys 1978a) and Auliciems (Auliciems 1981b). Moreover, there is a statistically significant relationship between the indoor neutral temperature and the indoor air temperature. Auliciems developed this theory and was the first researcher to propose the adaptive control algorithm (ACA) in 1986 and to present the equation relating to the outdoor air temperature's link with the indoor thermal comfort temperature. Related to the following studies (Auliciems and Dear 1986; CIBSE 2006; F. Nicol 1995; J.F. Nicol and Roaf 1996; J. Fergus Nicol et al. 1999), surveys of the indoor thermal comfort temperature in free-running buildings were developed by Humphreys, Nicol, Auliciems, de Dear, CIBSE and so on. The debate is that the rigorous restrictions of laboratory-induced environmental parameters are quite different from the actual field study of a real building environment (Auliciems 1989; Bouden and Ghrab 2005; Busch 1992; R. J. de Dear and Brager 2002). Moreover, the actual thermal comfort results express a difference when compared with those that the PMV model predicts. The field studies in naturally ventilated buildings expressed that the predictions calculated by the PMV model were predicting thermal sensations that are warmer than those which the occupants are actually feeling. In other words, the PMV model's predictions usually overestimate when predicting high temperatures and underestimate when predicting low temperatures in indoor environments (R. J. de Dear 1998).

The "Hot Summer and Cold Winter" (HSCW) zone has particularly extreme seasons of hot summer and cold winter. According to the local standard of residential building-design for energy saving in HSCW zones (Heldenbrand 1974), there is no central heating system and the prevention of uncomfortable overheating within the building environment is a main consideration of building-design criteria. It is claimed that indoor temperatures should be no higher than 28 °C for civil buildings in a HSCW zone (CNERCHS-PRC 2004; Heldenbrand 1974). Because the annual indoor air temperature is usually at around 10 °C without central heating equipment, the potential of overcooling problems are often overlooked in the building environment within this region. However, more and more occupants and local indoor-environment researchers are concerning themselves with the discomfort of freezing temperatures indoors during winter seasons. In particular, increasing requirements of living standards are gradually increasing the economic burden of energy-use spent on indoor heating. Adding the already existing energy problem of electricity use for cooling during summer, heating energy in a HSCW zone raised by 30.6% from 2003 to 2007 (NBSC 2004, 2005, 2006, 2007, 2008). The overheating and overcooling of residential buildings are two problems which drive this research on regional indoor thermal comfort. These problems are also a challenge for traditional thermal design in China, which is based on experimental calculation without any subjective people-participation. Although the thermal comfort and energy conservation are two sides of the same coin in sustainable building design, it is also reasonable to connect them together for keeping balance. The adaptive approach is a good method for the field study of thermal comfort research (Halawa and van Hoof 2012; Singh et al. 2011), and it helps us to understand that thermal comfort and energy efficiency do not completely depend on the building's physical environment of building material (insulation, shading, thermal mass and so on) or on the fitting of white goods or energy efficiency equipment; comfort and energy efficiency also depend on the region's subjective thermal preference of adaptation approaches. The empirical expectation of thermal experience, the social background impact (Race et al. 2010) and the design of the building's layout could all provide effective 'adaptation' for thermal comfort with an energy-saving capacity. Therefore, a variety of residential buildings in China would benefit from putting into practice the indoor thermal comfort research in terms of both cooling facilities during the hot summer and heating facilities for use in the cold winter.

Adaptive thermal comfort is a dynamic interactive process between subjective occupants and the objective building environment. As is well documented, the occupant has their own personal thermal expectation which is based on their own thermal experience, memory and physiological thermoregulation characteristics (Gail S. Brager and de Dear 1998b; J. F. Nicol and Humphreys 2002a). Therefore, this dynamic interactive process does not only include passive physiological reactions, but the human body could also present a positive reaction against the external physical stimuli. This positive reaction of adjustment mechanism is non-physiological, and is mainly composed of psychological and behaviour adaptations. When the environmental stimuli overload the personal thermal expectation, the personal thermal sensation could be experienced as an uncomfortable feeling. The common threshold of thermal comfort is defined by the ASHRAE seven-point scale. This is between negative and positive 1 (slightly cool and warm) in China (Wei et al. 2010) and 0.5 in the UK (CIBSE 2006). If the personal sensation of thermal comfort falls out of a person’s comfort range, heating or cooling facilities with low energy consumption can be used to restore the indoor environment to an acceptable temperature range. Consequently, it is crucial to investigate the occupants’ perception of the expected indoor thermal environment in a HSCW zone.

4.3 METHODS

The methodologies of this field study are mainly defined as a subjective questionnaire survey and objective on-site measurement. In this section, the theoretical framework, case study, questionnaire design and on-site measurement introduction are discussed separately.

4.3.1 THEORETICAL FRAMEWORK

The adaptive approach of thermal comfort is different from the theory of stable thermal transfer. People would flexibly adapt the thermal environment which they are exposed for thermal comfort. As the adaptive thermal comfort research suggests, the human physiological thermal sensation is usually effected by the adaptive coefficient, which is impacted by psychological adaptations and behavioural adaptations. Adaptation is a complex process which provides negative effects of “Adaptive Feedback” (R. Yao 1997) in the form of opening or closing a window for ventilation, taking off or putting on clothing, drinking hot or cooling water, and the psychological specifics of one’s socio-cultural background, education level and so on. Figure4.1 describes the complex process of adaptations, and it indicates the influence of behavioural adaptations and psychological adaptations in actual thermal sensation by the human body(R. Yao et al. 2009). The adaption mechanism is an exceedingly complicated process, and then the ‘Fuzzy Logic’ of ‘Black-box’ modelling is used to describe and understand the system and predict the real thermal sensation. As we know, the ‘’black box’ is defined as a device, system or object in science and engineering circle. There are only in terms of input, output and transfer characteristics can be viewed without detail of its internal working system. That is why we call its implementation is ‘black or opaque’. Moreover, ‘fuzzy logic’ is a kind of multiple-valued logic in the 'black-box' transfer system. As complicated as human's general thinking and semantic representation, there is not only take true or false values compared to traditional binary set. It has been extended to the concept of partial truth or false. For example of thermal sensation, first of all the human cognitive mechanism is opaque and then there are not only hot and cold (warm, slightly hot or cold and neutral point). Thermal comfort research is a typical fuzzy logic cognition.

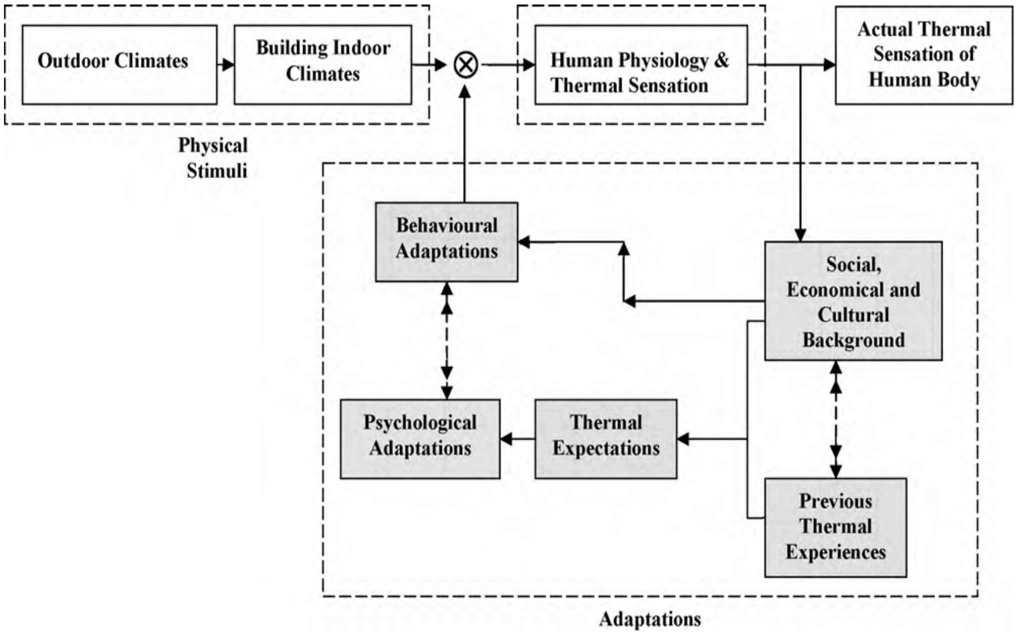


Figure4.1 The thermal comfort adaptive model mechanism.

The "Black Box" is the type of method used in cybernetics which presents the control mechanism of the system. In the early study of human thermal sensation, the environmental heating load had interaction with the human body, and the internal body thermoregulatory necessitates complicated physiological responses. These imbalances in thermal feelings are generally considered to be thermal sensation. As Fanger's research and application of international standard of ASHRAE 55-2010 and ISO7730 suggest, the steady state heat balance model uses the seven-point scale (ASHRAE scale) to describe the voting process from hot to cold (hot-warm-cool-cold). The deterministic logic graph is as follows(R. Yao 1997) in Figure4.2 (The deterministic logic is Physics-physiology-subjective thermal sensation):

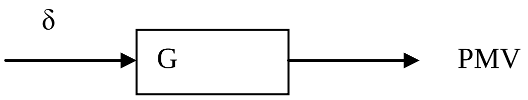


Figure4.2 Steady-state heat balance model of thermal comfort

- δ represents the physics stimulus from outdoor climates and indoor climates;
- G represents the human physiology of the thermoregulatory system and thermal sensation, which are usually referred to as the human body transfer function;
- PMV is the results of predicted mean vote;
- Equation of PMV:$\mathrm{PMV} = \mathrm{G} \times \delta$ --- (Equation4-1);

As the description of “Black Box”, it is the study to discover the logical and statistical relationships between the input and output of the complex process of the person’s thermal perception. According to the logic graph of Figure4.3, it is found that the system input is the external stimulus of the given thermal environment, and the system output is the person’s reaction caused by actual thermal sensation observed during the field study (R. Yao et al. 2009). The middle process is regarded as the human physiology of the thermoregulatory system and thermal sensation. However, in the field study within a real building environment, the middle process’s full operational details are quite complicated and are even partially unknown as they are based on the person’s own physiological, psychological and behavioural adjustment(The deterministic logic is from Physics to physiology, psychological and behavioural adaptations-subjective adaptive thermal sensation). Although a wide range of physical parameters of indoor environment are considered in the PMV-PPD model, it ignores the occupants, is not a passive recipient of thermal stimuli, and they have personal thermal expectation based on their own socio-cultural background. Their psychological and behaviour adaptation interact with each other in another “Black Box”, similar to the “Black Box” of the human physiological system (thermal sensation). These two complicated processes of “Black Box” interact with each other and related studies refer to ‘λ’ as the “adaptive coefficient”. The logic graph of the PMV model could be developed to be like the “Adaptive Predicted Mean Vote” (aPMV) model listed below:

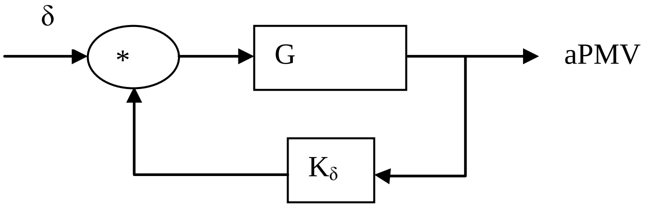


Figure4.3 Adaptive predicted mean vote model of thermal comfort

- δ represents the physics stimulus from outdoor climates and indoor climates;
- G represents the human physiology of the thermoregulatory system and thermal sensation, which is usually known as the human body transfer function;
- aPMV refers to the results of adaptive predicted mean vote;
- K_δ refers to the “Black Box” operational process of the psychological and behavioural impact coefficient;
- Equation of aPMV: $\mathrm{aPMV} = \mathrm{G} \times \delta - \mathrm{aPMV} \times K_\delta \times \mathrm{G}$--- (Equation4-2)

Then, $\mathrm{aPMV} = (\mathrm{G} \times \delta)/(1 + \mathrm{K}_{\delta} \times \mathrm{G})$---(Equation4-3)

Substituting equation (4-1) into equation (4-3),

Thena$\mathrm{PMV} = \mathrm{PMV}/(1 + \mathrm{K}_{\delta} \times \mathrm{PMV}/\delta)$ --- (Equation4-4)

- Assuming $\lambda = \mathrm{K}_{\delta}/(\delta)$, λ is defined as the adaptive coefficient, and the formula (4-4) is written as aPMV model:

  $\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1+\lambda\times\mathrm{PMV})}$---(Equation4-5)

The aPMV model is based on Fanger's steady-state heat-balance model (PMV model) and considers more adaptive approaches of psychological and behavioural adaptations from the results collected by Nicol et al, (J. Fergus Nicol et al. 1999), Sharma and Ali (Sharma and Ali 1986), and Busch et al (Busch 1992). According to Yao's cybernetics research of the "Black Box" logic graph and aPMV model equation derivation, the least square method is used to shorten the equation (5) and getting the adaptive coefficient "λ" Yao et al (R. Yao et al. 2009).

Let, x = 1/PMV and y = 1/aPMV, then the equation (4-5) can be transformed to:

$y = x + \lambda$ $\{y = f(x)\}$

Therefore, $\lambda = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n}$ --- (Equation4-6)

The theory of the equation of aPMV model is a very good explanation of the process of human reaction to the occurrence of ambient thermal discomfort. The aPMV model presented the relationship between aPMV and PMV, filling the gap in the results between the field surveys and rational laboratory experiments. This cybernetics concept is more generic than Fanger's PMV extension research(P.O. Fanger and Toftum 2002), which is only applicable to warm climates (R. Yao et al. 2009).

4.3.2 FIELD CASE STUDY

The field study has been launched in Yichang (Koppen-Cwa), which is located in the central part of a HSCW zone in China. In this part of the research, the aim is to find out the regional (HSCW) index of the adaptive coefficient λ based on the aPMV model for two different prototypes of residential apartment in China (see Figure4.4). The left section of the diagram below is case A, which has a longer depth unit layout with Y-axis room combination. The right section is case B which has a square unit layout with X-axis room combination. For these two cases the main building opening (glazing area) is designed on north-south. The building construction material is the same for both.

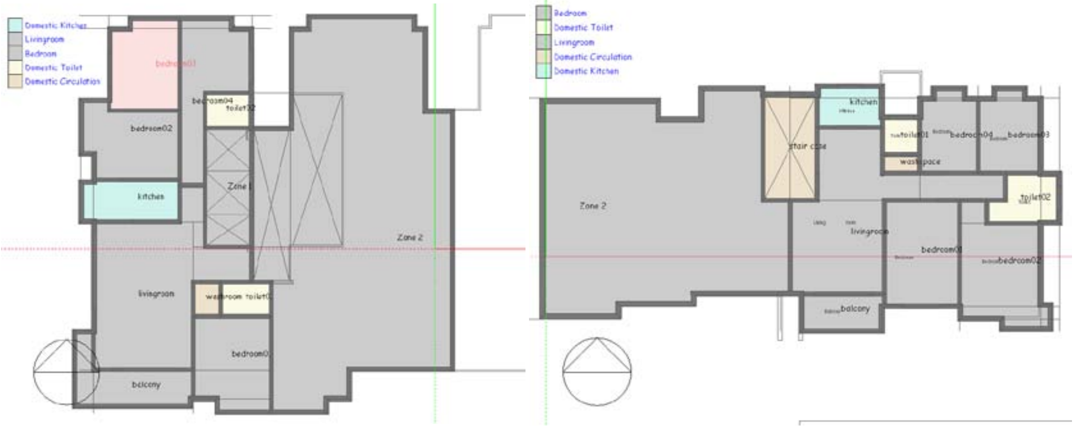


Figure4.4 The layout image of case A (left) and B (right)

A HSCW zone has two extreme seasonal weather situations of summer and winter and there are potential problems of overheating and overcooling for people’s indoor thermal environment design. Yichang is located in the central part of the HSCW zone, in the Hubei province of China, which has four clear seasons (spring, summer, autumn and winter) under the humid subtropical monsoon climate (MHURD-PRC and GAQSIQ-PRC 1993a). The specific classification is that of a humid subtropical climate in the Koppen climate classification – Cwa, when the driest winter month receives less than one tenth of the precipitation of the wettest summer month. In the hot summer the outdoor air temperature is usually in the range of 24.1-32.2^{o}C during July (extreme temperature above 41.4°C), and winter temperatures is usually recorded between 1.7-6.5 °C in January (with a 5% probability of reaching the extreme temperature of below -7 °C). The mean outdoor relative humidity during the whole year is around 75%. For reasons of history, there is no central heating system in the HSCW zone. For the design of indoor thermal environments, the energy-efficiency standard for residential buildings recommends the indoor thermal control of 26-28 °C for hot humid summer and 16-18 °C for cold winter. In the natural ventilation building (NV) the phenomenon of overheating and overcooling is a common occurrence. The typical residential apartment in the HSCW zone is designed with NV, and actual indoor thermal control is equipped with a split-type air conditioner and supplemented with a portable electric heater or chiller. Consequently the large amount of electricity used impacts occupants’ living costs, especially in summer and winter.

4.3.3 QUESTIONNAIRE SURVEY DESIGN

The subjective questionnaire survey aims to find out the occupants' mean preference for their indoor thermal sensation which includes three indexes. The first index is thermal experience (Te) preference which is measured on a seven-point scale based on the thermal sensation Bedford scale or 'comfort vote' in ASHREA standard (J. F. Nicol and Humphreys 2002a). The secondary index is overall comfort (Oc) preference which is a comfort assessment range within a five-point scale. '0' means comfortable, '2' and '4' stand for uncomfortable and extremely uncomfortable respectively, and '1' and '3' stand for the medium level between the uncomfortable perception of '0-2' and '2-4'. The third index is a thermal tolerance (Tt) preference. This is also measured on a five-point scale with '0' reflecting the perfectly bearable tolerance, '2' and '4' stand for fairly difficult to tolerate and absolutely intolerable. The '1' and '3' stand for the medium level of thermal tolerance between the range of '0-2' and '2-4'.

The questionnaire survey is designed to collect the participants' thermal sensation preference of AMV. Following the survey sample mentioned in ASHRAE 55-2010 Informative:

- Interviewee's background information, such as age, gender, etc. In the summer time there were 20 participants involved in the on-site measurement and 22 participants in winter seasons. All participants are healthy Chinese nationals living in one of the two residential communities (cited in Chapter Three) of similar prototypes of case A and B for over one year. There are approximately 42% male and 58% female participants. The average age is controlled at around 40 years.
- Interviewee's clothes and metabolic rate (real-time activity). The clothing insulation is different during the hot summer and cold winter, however there is no significant difference across participants in summer or winter. They are requested to avoid indoor furniture which has a high insulation level, for example the leather sofa, as such forms of other insulation can effect results and are easily neglected when calculating clothing insulation. The questionnaire survey is a real-time data collection, and consequently the occupants' indoor activities are a real-time parameter which are recorded at the same time as their thermal sensation preference. The residential environment is a place for diverse human activity. This could effect the results of the thermal sensation survey depending on the ranges of activity. The metabolic rate of real-time occupants' activity refers to ASHRAE 55-2010 normative appendix A and Table B1 and B2, which are attached on the preface page of the survey's recording sheet.

- Interviewee’s actual thermal experience perception – actual mean vote (AMV). It is an extension PMV value by directly assessing personal thermal reflection. It refers to the ASHRAE seven-point thermal sensation scale which enables the participant to provide a simple description about their personal thermal preference in the testing time. It is defined with three points on both sides of 0, with 0 representing ‘just right’ (neutral), -3 cold, -2 cool, -1 slightly cool and 1slightly warm, 2 warm and 3 hot, respectively.
- Interviewee’s overall comfort sensation. The thermal sensation is the evaluation of the ambient thermal environment quality of warm or cool. The comfort sensation feedback is based on the 5-point scale: 0 comfortable (neutral), 1 slightly uncomfortable, 2 uncomfortable, 3 very uncomfortable and 4 extremely uncomfortable.
- Interviewee’s thermal tolerance capability. This relates to the personal preference of the participants’ capability to tolerate uncomfortable indoor environmental stimuli and, similar to the overall comfort scale, it is based on 5-points: 0 able to completely tolerate, 1 almost acceptable to endure, 2 hard to endure, 3 more difficult to endure, 4 extremely intolerable,

4.3.4 ON-SITE MEASUREMENT

The survey of on-site measurement is composed of two sections. The first measures and records the participants’ results on thermal sensation. The data collection is related to the PMV model’s calculation, based on Fanger’s equation. PMV value is a prediction based on a calculation by using measured input parameters. The data measurement of the PMV calculation synchronises with the questionnaire of person’s sensation records (AMV) in duration for a continuous four or five testing days. There are 20 participants in the field study in each extreme season (overheating in summer and overcooling in winter), and ten for each prototype case. They are required to record their indoor thermal responses 2-3 times in each testing day and, moreover, for each time the thermal responses are recorded, the records are separated into the first half time and once again in the middle of the next half time (total of an hour for one testing time). The use of PMV is calculated by using four on-site measured inputs of air temperature, mean radiant temperature, relative air velocity and relative humidity, and two on-site records of real time activity level and real time clothing value.

The study is helpful to calculate the 'adaptive' coefficient 'λ' for the regional (HSCZ zone) discrepancy regularity between the actual subjective thermal sensation actual mean vote (AMV) and the calculation of the empirical PMV model for residential buildings. The actual PMV model would be used to present the regional adaptive coefficient of the HSCW zone for the prototype residential apartment in China. The other on-site measurement is taken using equipment which monitors the process. The 'HOBO' logger records the indoor air temperature and relative humidity during the whole field study time and this increases when covering the hot summer and cold winter months. HOBO loggers were set in these two selected cases. They are equipped with a split-type air-conditioner and are assisted with a low-powered removable heating/cooling facility. The HOBO logger is located at the height of 1.1m, which is near to head-level when an average-sized Chinese adult is seated. The monitoring period covered the time of subjective response in the field study during the hot summer and cold winter. There are nearly one and half months constituting summer (22/07/2011-02/09/2011) and nearly three months for winter (14/11/2011-12/02/2012) in both of the selected cases. The monitoring measurement presents the indoor thermal environment records for these two selected cases. The data analysis helps to estimate the potential problems of overheating and overcooling under the 'mixed mode control' by applying the air conditioners and small power heating or cooling facilities.

4.4 THE SUMMARY OF FIELD STUDY

The statistical summary of indoor environmental parameters is shown as following part (see Table 4.1, 4.2 4.3 4.4 for summary statistic data, Appendix C provide correlation analysis and significance test results). The statistic summary of the field study is composed by three parts namely are participants' factors (clothing and metabolic activity level), thermal environmental parameters and the human thermal response records (PMV, PPD, AMV, Overall comfort and Thermal tolerance).All the parameters are based on subjective questionnaire survey and synchronous on-site measurement except the PMV and PPD that are calculated by PMV-PPD model computer program. It was edited as MATLAB program with excel document input and getting excel output. All the data collection focused on the indoor condition for two prototypes of case A and case B, which are controlled by mixed mode. All the questionnaire survey and real-time measurement for several thermal parameters were launched under the situations of equipment control power-off at least one hour before the each testing hour start.

Table4.1 Summary of thermal parameters data collection in summer of case A

Hot summer, case A						
Parameters	**Unit**	**N**	**Min.**	**Max.**	**Mean**	**S.D.**
Cloth	Clo.	365	0.20	0.70	0.37	0.11
Metabolic rate	M	365	0.70	2.20	1.46	0.53
T_{ia}	°C	365	26.00	33.50	30.76	1.66
T_{imr}	°C	365	27.00	34.80	31.67	1.66
RH_i	%	365	46.4	78.6	61.50	6.75
V_i	m/s	365	0.00	1.50	0.10	0.25
PMV	-	365	0.02	3.25	2.17	0.55
PPD	%	365	5.00	99.77	79.69	21.78
AMV	-	365	0	3	1.62	0.62
Oc	-	365	0	4	1.49	0.87
Tt	-	365	0	3	1.13	0.88

Table4.1 presents a statistical summary of case A for hot summer, the clothing insulation rates were recorded in the real-time field study for the interviewees’ garment status, different people wore few different clothing. The clothing range was around 0.2clo and 0.7clo, with mean value of 0.37clo. The M value stand for the metabolic rate based on the participants’ activity status (based on the ASHRAE 55-2010 activity level guideline) with its duration effect, for example in an half hour there are15 minutes on reading (1.0 met) and the other half is on standing (1.2 met), thus the testing result is calculated by the equation of 0.5×1.0+0.5×1.2 = 1.1 met. The statistical summary indicates the lowest metabolic rate was 0.7 met and the highest record was 2.20 met, and the mean value was 1.46 met. For the indoor physical environment summary the highest indoor air temperature is 33.50°C and the lowest temperature was 26 °C with the mean value of 30.76 °C. we can see that without the mechanism adjustment (equipment working) the lowest value was above the indoor air temperature control recommended by local housing standard upper limitation of 28 °C, that means the overheating phenomenon could happen in case A under the hot summer season. The mean value of indoor relative humidity (RH) was 61.5% with the range between 46.4% and 78.6%. The indoor air velocity was average at 0.1 m/s by opening external window for natural ventilation with discontinuous external wind.The thermal response records are respectively based on PMV-PPD model calculation program and AMV voting results collection. The mean value of PMV was 2.17 with 79.69%. These results implied that the PMV thermal sensation over the ‘warm’ definition in ASHRAE standard scale (2) and nearly 80% people are deemed to feel discomfort with dissatisfaction vote in case A. However the actual mean vote records indicated a lower mean value of 1.62. The mean value of overall (thermal) comfort (Oc) is 1.49, and the participants’ thermal tolerance (Tt) mean value was 1.13 of just over slightly difficult to bear in case A. The thermal response records indicate that PMV-PPD model overestimate occupants’ thermal sensation with narrow range of acceptable thermal comfort.

Table4.2 Summary of thermal parameters data collection in summer of case B

Hot summer, case B						
Parameters	**Unit**	**N**	**Min.**	**Max.**	**Mean**	**S. D.**
Cloth	Clo.	362	0.30	0.50	0.48	0.06
Metabolic rate	M	362	0.80	2.10	1.40	0.51
T_{ia}	°C	362	25.00	32.60	28.57	1.75
T_{imr}	°C	362	26.40	33.80	29.63	1.77
RH_i	%	362	48.1	84.5	68.15	8.92
V_i	m/s	362	0.00	5.00	0.23	0.55
PMV	-	362	-1.04	3.32	1.40	0.91
PPD	%	362	5.00	99.85	50.23	31.96
AMV	-	362	0	3	1.13	0.74
Oc	-	362	0	3	1.08	0.87
Tt	-	362	0	3	.86	0.84

Table4.2 presents a statistical summary of case B for hot summer, the clothing rates’ range is between 0.3clo and 0.5clo with the mean value of 0.48clo. The metabolic rates were collected between 0.8 met and 2.1 met with the mean value of 1.4 met. For the physical environment parameters measurement, the highest temperature in summer reached 32.6 °C and the lowest temperature was 25.0 °C, and the mean value was 28.57 °C. The indoor air temperature of case B was somewhat lower than that recorded in case A. The indoor RH values of case B were between 48.1% and 84.5%, and the men value was 68.15%.The RH level of case B was nearly equal the level of case A, it was around upper limit of China healthy housing standard of 70%. The indoor air velocity values of case B were between 0 m/s and 5.0 m/s, and the mean value is 0.23 m/s. because of the prototype layout in case B, there are more natural ventilation of a crossing draught from inside to outside by external window open and easily record extreme value of indoor air velocity. According to the thermal response records, the mean value of PMV was 1.40 with 50.23% of PPD value, which was great lower than these values of case A. In other words, occupants’ thermal perception of case B was around slightly warm and nearly half of people are predicted to vote thermal dissatisfaction. The mean value of overall (thermal) comfort was 1.08, which was lower than that of case A. The mean value of Tt was 0.86 just nearly reach the level of slightly difficult to bear.

Table4.3 Summary of thermal parameters data collection in winter of case A

Cold winter, case A						
Parameters	**Unit**	N	Min.	Max.	Mean	S. D.
Clo.	**Clo.**	352	1.14	1.36	1.28	0.04
M	**M**	352	1.00	1.00	1.00	0.00

T_{ia}	**°C**	352	10.20	20.60	13.34	1.90
T_{imr}	**°C**	352	10.60	21.40	14.16	1.85
RH_i	%	352	33.5	84.0	51.97	8.40
V_i	**m/s**	352	0.00	0.00	0.00	0.00
PMV	-	352	-2.61	-0.23	-1.85	0.43
PPD	%	352	6.05	95.42	67.77	19.90
AMV	-	352	-3	-1	-1.43	0.62
Oc	-	352	0	4	2.04	0.81
Tt	-	352	0	3	1.55	0.75

Table4.3 presents a summary of the cold winter field study in case A. The winter clothing insulation range is between 1.14clo and 1.36clo, and the mean value is 1.28clo. The respondent indoor activity in winter field study was fixed on quiet seating, thus the metabolic rate of quiet seating is 1.0 met referred by ASHRAE 55-2010 Appendix A. During the winter field study the lowest indoor air temperature in case A was 10.2 °C and the highest indoor air temperature was 20.60 °C, and the mean value of indoor air temperature was calculated at 13.34 °C. The indoor mean radiant temperatures close to the air temperatures. The RH values were similarly separated into indoor and indoor measurement records. The lowest value of indoor RH was 33.5% and the highest value was 84.0%, and the mean value of indoor RH was 51.97%. The air movement is a key parameter to increase the heat lost around human body, in the winter of indoor case A the air velocity was zero in the ambient of testing point (interviewees' seating point located in the middle part of the testing space) means there was no obviously huge air movement around the testing point. Under this cold winter conditions of case A the PMV calculation range was between -2.61 and -0.23, and the mean value was -1.85. That means the participants in case A were predicted to vote nearly warm level of thermal sensation scale. The corresponding PPD calculation values had fluctuations with the lowest value of 6.05% and the highest dissatisfaction of 95.42%. However the AMV records provided the fluctuation between the lowest scale of -3 (cold) and highest level of -1 (slight cool) and the mean value was -1.43. The personal overall thermal comfort votes were between 0 and 4 with the mean value of 2.04. That results implied that interviewees felt uncomfortable in their exposed environment. For the thermal tolerance vote, the range was between zero and 3 (very difficult to bear) and the mean value was 1.55 which is located middle point between slightly difficult to bear and the level of fairly difficult to bear.

Table4.4 Summary of thermal parameters data collection in winter of case B

Cold winter, case B						
Parameters	**Unit**	**N**	**Min.**	**Max.**	**Mean**	**S. D.**
Clo.	Clo.	292	1.22	1.52	1.42	.08
M	M	292	1.00	1.00	1.00	.00

T_{ia}	°C	292	7.20	13.70	10.27	1.58
T_{imr}	°C	292	7.50	16.20	11.15	1.66
RH_i	%	292	31.9	78.9	56.85	10.10
V_i	m/s	292	0.00	0.00	0.00	0.00
PMV	-	292	-3.29	-1.71	-2.54	0.37
PPD	%	292	62.06	99.83	91.35	7.86
AMV	-	292	-3	-1	-2.23	0.58
Oc	-	292	1	4	2.75	0.59
Tt	-	292	1	4	2.32	0.64

According to the statistic summary of case B listed in Table4.4the clothing rate range was between 1.22clo and 1.52clo, and the mean value of winter clothing insulation rate in case B was 1.42clo. The activity level at the time of testing got a stable value of 1.0 met under quiet seating conditions for writing survey or charting with me. As the indoor thermal parameters measurement records the minimum indoor air temperature was 7.2 °C and recorded maximum indoor air temperature was 13.70 °C, and the mean records was 10.27 °C. For the indoor mean radiant temperature records the lowest value was 7.5 °C and the highest value was 16.20, and the mean value is 11.15 °C. The indoor RH range was between 31.9% and 78.9%, and the mean value is 56.85%. The indoor air velocity range got the value of zero without any sensible air movement. As the thermal environment of case B in winter survey time the PMV model calculated the minimum sensation value of -3.29 and the maximum voting value was -1.71. The mean value is -2.54. In accordance with the PMV-PPD calculation, the PPD range got the fluctuation of dissatisfaction between 62.06% and 99.83%, and the mean value is 91.35% with such high level of dissatisfaction. In this winter field study the actual mean vote records indicated the minimum value was -3 and the maximum value was -1, and the mean voting is -2.23. It is means that subjective thermal sensation has relative higher value with warmer feeling and the deviation is lower than that in case A. For the participants' subjective assessment of overall thermal comfort, the voting fluctuation was between 1 and 4 with the mean value of 2.75. It is nearly close to the level of very uncomfortable. The participants' tolerance capacity vote got the fluctuation between 1 and 4 with the mean value of 2.32 which reach the middle point level between the level of fairly difficult to bear and the level of very difficult to bear.

4.5 THE POTENTIAL OF INDOOR OVERHEATING AND OVERCOOLING

According to the design standard for the energy efficiency of residential buildings in the HSCW zone (Heldenbrand 1974), and the technical essentials for construction of healthy housing (CNERCHS-PRC 2004), the threshold values of indoor thermal environments are designed to prevent overheating and overcooling. 28 °C is usually considered as the upper limit of thermal comfort in design and 16 °C is the lower limit for energy efficiency of residential buildings, whilst 18 °C is the lower limit for healthy housing in China. However there is no clear definition for what precisely constitutes overheating or overcooling for building environments in China. According to the definition provided in research from the UK (Race et al. 2010), '*…for the individual, the overheating is defined [as when] that indoor temperature rises to a level that the individual feel[s is] unacceptably uncomfortable. For the occupants as a whole, overheating can be related to the upper limit of the comfort temperature band…*', therefore the definition of overheating could be summarised as when '*…the actual indoor temperature for any given day exceeds the upper limit of the comfort temperature range for that day by enough to make the majority of people feel uncomfortable…*' (Race et al. 2010). In this study the margin of overheating and overcooling is defined as upper and lower limits of the environment designing range for China's residential buildings located in the HSCW zone (see Table4.5).

Table4.5 China's residential building standard for indoor environment design

Coefficient of healthy housing	**Unit**	**Standard value**	**Note**
Temperature	°C	24-28	Summer
	°C	18-22	Winter
Relative humidity	%	30-70	N/A
Coefficient of energy efficiency	Unit	Standard value	Note
Temperature	°C	26-28	Summer (L[1] and B[2])
	°C	16-18	Winter (L and B)
Relative humidity	%	N/A	N/A

1.L-living room;
2.B-Bedroom;

Table4.6 Overheating and overcooling study in case A and B during the summer and winter

Case A-summer		**Overcooling**		**Total**	**Overheating**	**Min. (°C)**	**Max. (°C)**	**Mean (°C)**
		16 (°C)	**18 (°C)**		**28 (°C)**			
Living room	**Samples**	None		6075	**4086**	25.22	36.73	29.54
	Percentage			100%	**67.26%**			
	Hours			1012	**680.67**			
Case B-summer								
Living room	**Sample**	None		6075	**3471**	23.77	31.06	27.94
	Percentage			100%	**57.13%**			
	Hours			1012	**578.16**			
Case A-winter		**Overcooling**		**Total**	**Overheating**	**Min. (°C)**	**Max. (°C)**	**Mean (°C)**
		16 (°C)	**18 (°C)**		**28 (°C)**			
Living room	**Samples**	**5629**	**7604**	8711	None	10.26	26.29	14.89
	Percentage	**64.62%**	**87.29%**	100%				
	Hours	**1399.35**	**1890.26**	2165.5				
Case B-winter								
Living room	**Sample**	**7242**	**8002**	8711	None	6.57	19.79	11.44
	Percentage	**83.14%**	**91.86%**	100%				
	Hours	**1800.40**	**1989.23**	2165.5				

The data collection in this section is based on continuous monitoring record by application of HOBO device (the detailed technical description is mentioned in the Chapter 3), and Table4.6 displays overheating or overcooling occurred in both cases during the hot summer time or cold winter always over half of monitoring time. The overheating percentage rate of case A (67.26%) was greater than that of case B (57.13%). For the winter time survey the overcooling dominated the inside thermal environment. Both cases' indoor thermal environment can barely reach the lower limit of China's healthy housing (18 °C) and nearly 90% of data collected during the recording time was detected as being in an overly-cool condition. Compared with the lower limit of energy efficient residential building (16 °C) the percentage of overcooling was reduced to 65% in case A and 83% in case B.

4.6 THE REGIONAL THERMAL SENSITIVITY

The indoor discomfort environment is a description of an environment which is overheating or overcooling and which has external negative stimuli which impacts upon occupants' indoor productivity and health. This usually occurs during a hot humid summer and damp cold winter in a HSCW zone, and occupants can represent their thermal-preference responses based on the ASHRAE seven-point scale for the acceptable indoor air temperature range. According to the related studies (M. A. Humphreys 1976; J. F. Nicol and Humphreys 2002a),‘*The air temperature is one of the most direct indexes of thermal environmental assessment’* and usually a quantified thermal sensation vote using the ASHRAE scale has a significant correlation with the air temperature based on the linear regression equation. Figure4.5 shows the PMV model calculation and AMV questionnaire record in case A of the field study. Figure4.6 displays the results of comparison between the PMV model and the AMV model in case B. The trend-line of the PMV and AMV indicate similar results to those of Nicol; the PMV model’s prediction always overestimates the occupants’ thermal response (AMV) during the hot summer and underestimates the value at low indoor air temperature in winter, whether in the prototype of case A or case B.

The slopes of the two equations indicate the occupants’ thermal sensitivity change alongside the indoor air temperature change (R. Yao et al. 2009). This means that if the indoor air temperature changes by one unit in degrees Celsius the adaptive thermal sensation would change in equal values of thermal sensation, and the value of the slope can be defined as the occupants’ thermal sensitivity towards the ambient environment. In Figure4.5, the occupants’ thermal sensitivity of the PMV model and the AMV model are 0.284 unit/°C and 0.184 unit/°C respectively. The research found that the occupants’ thermal sensitivity of the PMV model is stronger (with more unit changes of the ASHRAE thermal sensation voting scale) than that of the AMV. As the equations (4-7) and (4-8) show, the reciprocal of slope indicate that each sensation change is derived by the extent of the indoor air temperature change. According to these two slopes of observation, the correlation of the sensation scale to the temperature range of the PMV model is 3.5°C/unit which is less than that of the AMV model, which is 5.4°C/unit. This result suggests that the occupant has a border-line tolerance range to the increase of the temperature indoors using the AMV model than that calculated by the PMV model.

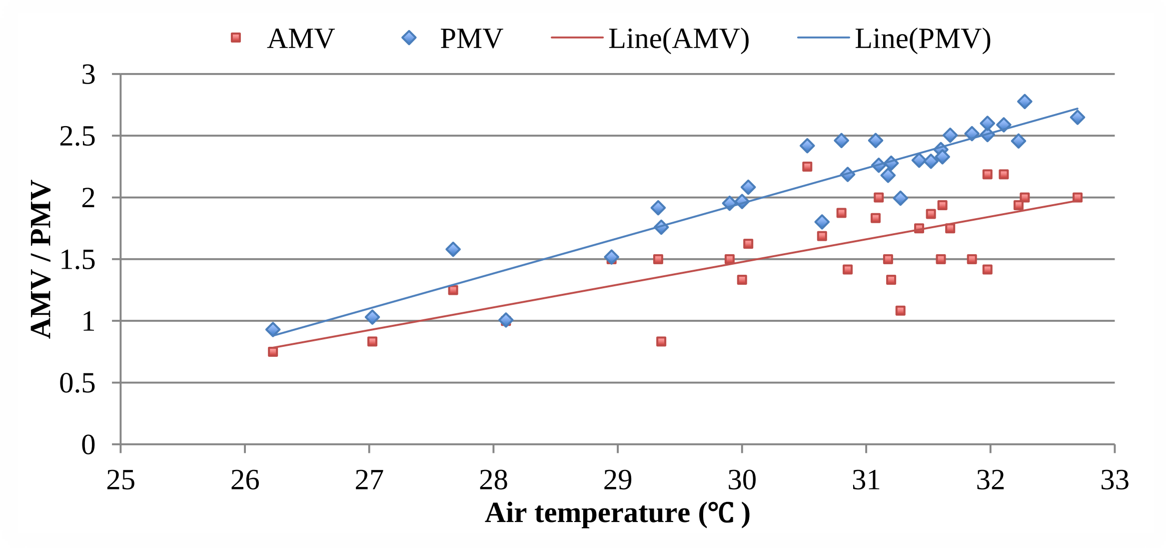


Figure4.5 The PMV model calculation results and actual mean vote in Case A in the hot summer in Yichang, China.

$PMV_A = 0.284T_{ia} - 6.57$ ($R^2 = 0.88$) --- (Equation4-7)

$AMV_A = 0.184T_{ia} - 4.04$ ($R^2 = 0.53$) --- (Equation4-8)

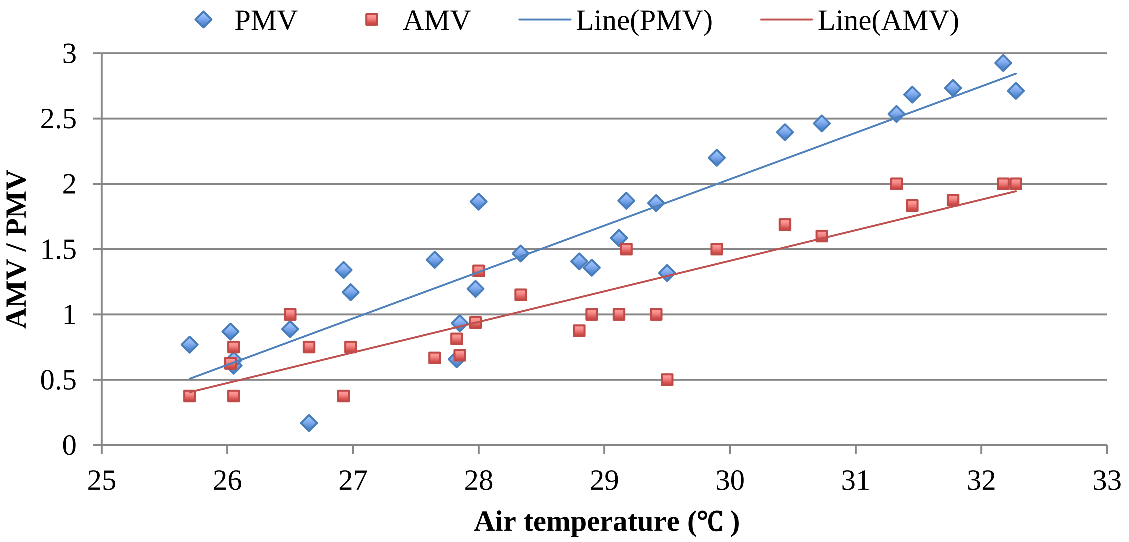


Figure4.6 The PMV model calculation results and actual mean vote in Case B in the hot summer in Yichang, China.

$PMV_B = 0.356T_{ia} - 8.628$ ($R^2 = 0.86$) --- (Equation4-9)

$AMV_B = 0.234T_{ia} - 5.717$ ($R^2 = 0.78$) --- (Equation4-10)

As the illustration of linear regression shows in Figure4.6, the occupants' thermal sensitivity of the PMV model and the AMV model is recorded at 0.356 unit/°C and 0.234 unit/°C respectively. The research found that the occupants' thermal sensitivity of the PMV model is stronger (significant unit changes of the ASHRAE thermal sensation voting scale resulting in air temperature change) than that of the AMV model. As equations (4-9) and (4-10) show, the reciprocal of slope indicates that each sensation change is derived from the extent of the indoor air temperature change. According to these two slopes of observation, the relationship of the sensation scale to the temperature range of the PMV model is 2.8°C/unit which is less than that of the AMV model which is 4.3°C/unit. This result suggests that the occupant has a border-line tolerance range to the increase of the temperature indoors with the AMV model than that calculated by PMV model.

In Figure4.7 the slopes of the PMV and AMV models indicate the respondents' thermal sensitivity whilst indoors during the cold winter conditions in case A. The equations(4-11) and (4-12) display the slope of PMV model is 0.225 unit/°C and AMV indicates a 0.173 unit/°C slope for matching the indoor air temperatures. The PMV model is stronger than that of the AMV. As the reciprocal slope demonstrates, every unit change of the PMV model's predicted vote is to the value of a 4.4 °C decrease, whilst the AMV model's predicted vote is to the value of a 5.8°C decrease in case A. In Figure4.8, the PMV model likewise has a more significant slope than that shown by the AMV equation. This means that the PMV model underestimates the participants' response at low temperatures in the prototype of case B. The slopes of equations (4-13) and (4-14) are represented at 0.238 unit/°C and 0.199 unit/°C respectively. The indoor air temperature decreases by 4.2 °C/unit and 5.0°C/unit respectively with the predicted vote change.

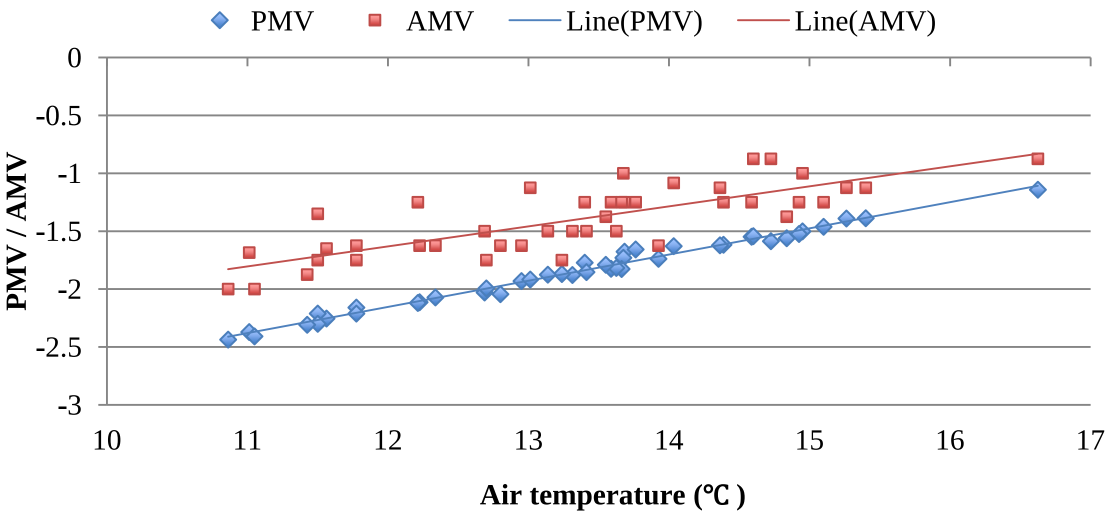


Figure4.7 The PMV model calculation results, and the actual mean vote in Case A in the cold winter in Yichang, China.

$PMV_A = 0.226T_{ia} - 4.869$ ($R^2 = 0.98$) --- (Equation4-11)

$AMV_A = 0.173T_{ia} - 3.708$ ($R^2 = 0.63$) --- (Equation4-12)

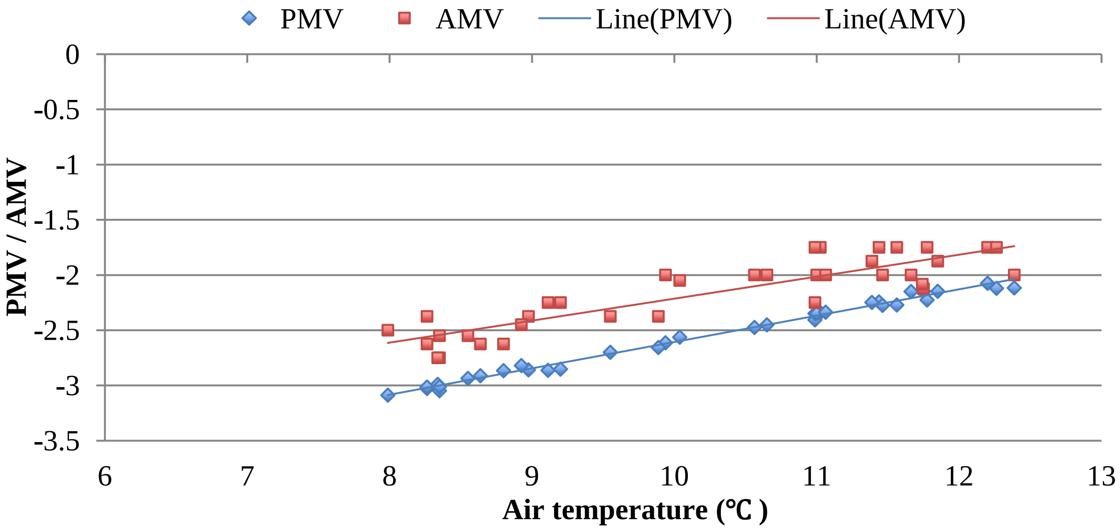


Figure4.8The PMV model calculation results and actual mean vote in Case B in the hot summer in Yichang, China.

$PMV_B = 0.238T_{ia} - 4.990$ ($R^2 = 0.99$) --- (Equation4-13)

$AMV_B = 0.199T_{ia} - 4.205$ ($R^2 = 0.78$) --- (Equation4-14)

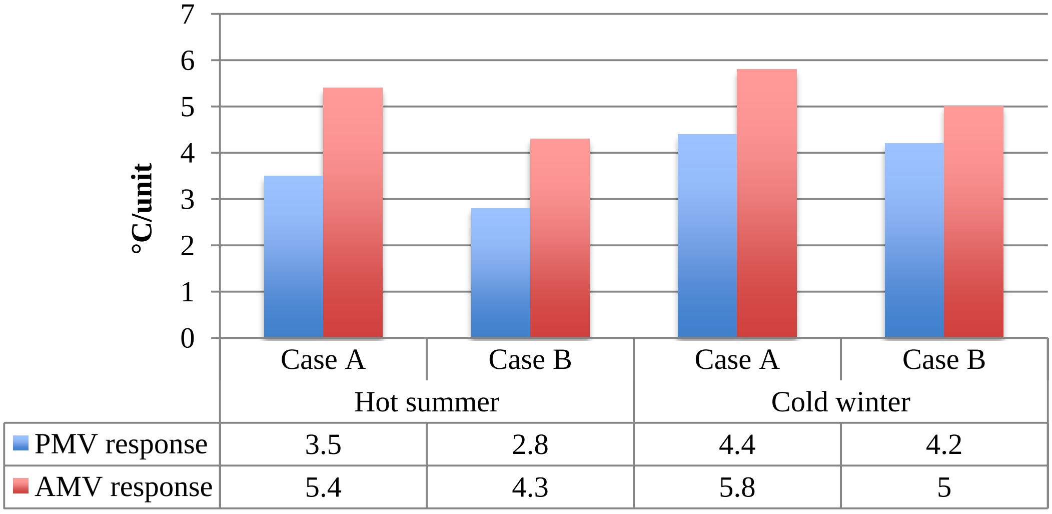


Figure4.9 The Thermal response of two cases in the HSCW zone.

To summarise the tolerance levels towards indoor air temperature change (see Figure4.9), the research results show that respondents can tolerate a wider changing range of indoor air temperatures with the AMV model than they can based on the PMV model, whether in the prototype of case A or case B. The tolerance range of the changes in indoor air temperature during the hot summer are usually less than those which occurred in winter time whether in the prototype of case A or case B. In other words, local occupants have a higher level of thermal sensitivity in warmer indoor conditions than they do for indoor conditions during colder months in both cases.

4.6.1 THE REGIONAL ADAPTIVE COEFFICIENT

Following on from the thermal responses of the field study participants, the data sets of the two extreme seasons of the hot summer and cold winter are obtained from a real indoor residential building environment in a HSCW zone of China. For the same level of indoor temperature, it is found that the AMV values are always lower than those for the corresponding values based on the PMV model's calculation in hot summer, and that they are greater than those of the PMV model in the cold winter time. These findings match similar results of those from other field studies (Becker and Paciuk 2009; Bouden and Ghrab 2005; Corgnati et al. 2009; Ogbonna and Harris 2008). That phenomenon is due to the human adjustment mechanism of the thermal adaptation process. Occupants restore their thermal comfort when they receive stimuli which is considered to have an overheating impact in summer and an overcooling impact in winter before they use a household facility of mechanical thermoregulation (J. Liu et al. 2012b). That mechanical thermal control is usually achieved by using air-conditioning or some other low-power chiller or heater (MHURD-PRC 2010), with the energy use of these devices reflected by the electricity or gas bill. Therefore the regional adaptive coefficient is an important reference for the regional indoor adaption level based on the local climate and socio-cultural setup, and the most significant point is to provide a dynamic process for indoor energy use by set-point control of indoor air temperature based on the adaptive approach. This adaptive method will verify the thermal comfort standards in the local context like some studies developed by Becker et al (Becker and Paciuk 2009) and Bouden et al (Bouden and Ghrab 2005).

As the thermal sensation logic formulas presented in equations (4-1) to (4-6), the least square method has been used to calculate the adaptive coefficient of the 'λ' value. The PMV model's calculation results and those of the AMV model are defined as pairs of inputs (x, y). The (x, y) function curve is deviated by the least square method to fit each pair of data points. For each seasonal field study (whether summer or winter), there are 31 sets of data during summer time in case A, 28 sets during summer time in case B, 43 sets of data during winter in case A and 36 sets during winter in case B.

By using the equation (4-6), the adaptive coefficients for two prototypes of cases in summer and winter are calculated. Equations (4-15), (4-16), (4-17) and (4-18) below are dragged into the adaptive coefficient formula:

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1+0.174\times\mathrm{PMV})}$---(Summer time in case A)--- (Equation4-15);

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1+0.215\times\mathrm{PMV})}$---(Summer time in case B)--- (Equation4-16);

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1-0.192\times\mathrm{PMV})}$---(Winter time in case A)--- (Equation4-17);

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1-0.072\times\mathrm{PMV})}$---(Winter time in case B)--- (Equation4-18);

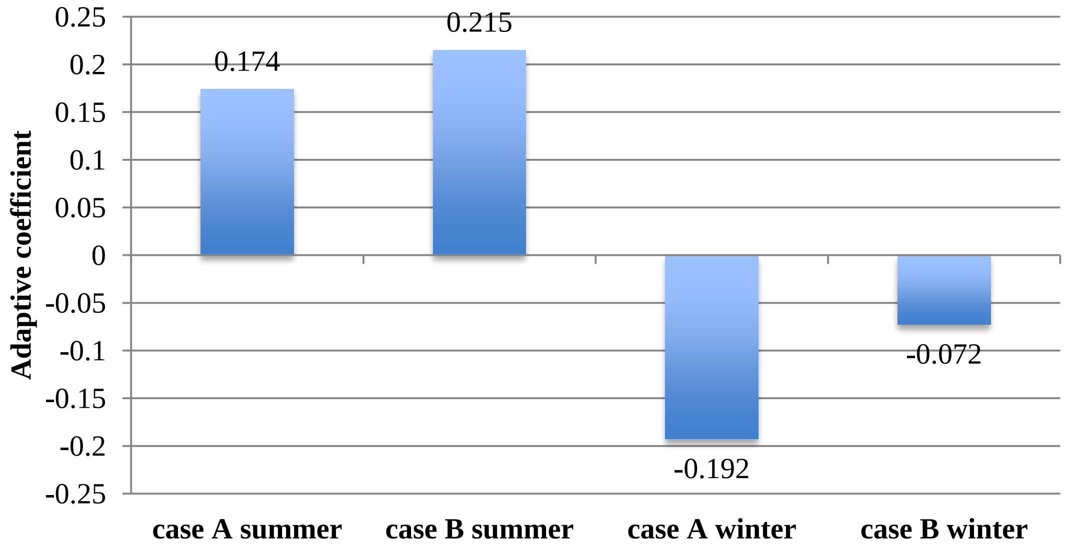


Figure4.10 The adaptive coefficients of two prototypes of case A and B under hot summer and cold winter.

The adaptive coefficients are listed in Figure4.10. It is observed that the adaptive coefficient values are positive during the warm conditions (hot summer) and negative throughout the cold conditions (cold winter). The positive values mean that subjective corrections increase one's tolerance capability to hot situations, which shows lower discomfort to the heat preference than that calculated by the PMV model. In other words, after applying the "Black Box" of the adaptation process (psychological and behavioral adaptation), people feel less hot than the heat balance model of the predicted index, and thermal respondents' actual sensation votes (aPMV) are lower than the PMV model's for the same thermal environment. The reverse situation occurs in winter, the adaptive coefficient is presented as a negative value and the aPMV value is higher than the PMV value for the same indoor cooling environment. Occupants feel less of a cooling sensation than that predicted by the PMV model. These findings are similar to those in Yao's studies (R. Yao et al. 2009; R. Yao et al. 2010) on classroom thermal environment in Chongqing, another HSCW zone of the China, and Singh's field study of adaptive thermal comfort in North-East India (Singh et al. 2011).

According to the adaptive coefficient values mentioned for these two cases of prototypes, it is observed that the 'λ' value of case B (0.215) is higher than that in case A (0.174) in hot summer time. In the cold winter the 'λ' value of case B (-0.072) is higher than that in case A (-0.192). The 'λ' value is calculated by equation (4-5) and is represented below:

$x = 1/PMV$ and $y = 1/aPMV$, thus $y = x + \lambda$ $\{y = f(x)\}$--- (Equation4-19)

Then, $\lambda = y - x$--- (Equation4-20)

In the warm time:

$\lambda > 0$ If $\lambda_A < \lambda_B$, then $y_A < y_B$

When $PMV_A = PMV_B$

$aPMV_A > aPMV_B$

In the cold time:

$\lambda < 0$, If $\lambda_A < \lambda_B$, then $y_A < y_B$

When $PMV_A = PMV_B$

$aPMV_A > aPMV_B$

According to the derivation study mentioned above it is found that when the steady-states heating model of PMV calculate a similar result, the adaptive thermal comfort model – aPMV - would get the results of $aPMV_A > aPMV_B$. This shows that the thermal environment of case A always makes people feel warmer than that of case B whether it is hot summer or cold winter. It means that the prototype of case A is more suitable for cold winter than case B, and case B is more suitable for overheating in summer than case A.

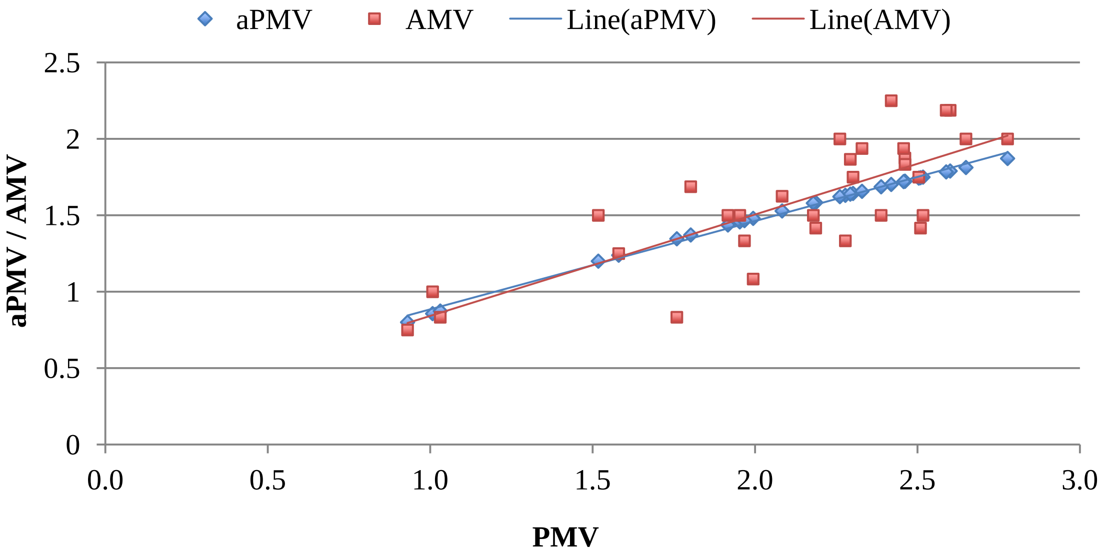


Figure4.11The relationship between PMV, aPMV and AMV for hot summer conditions in case A

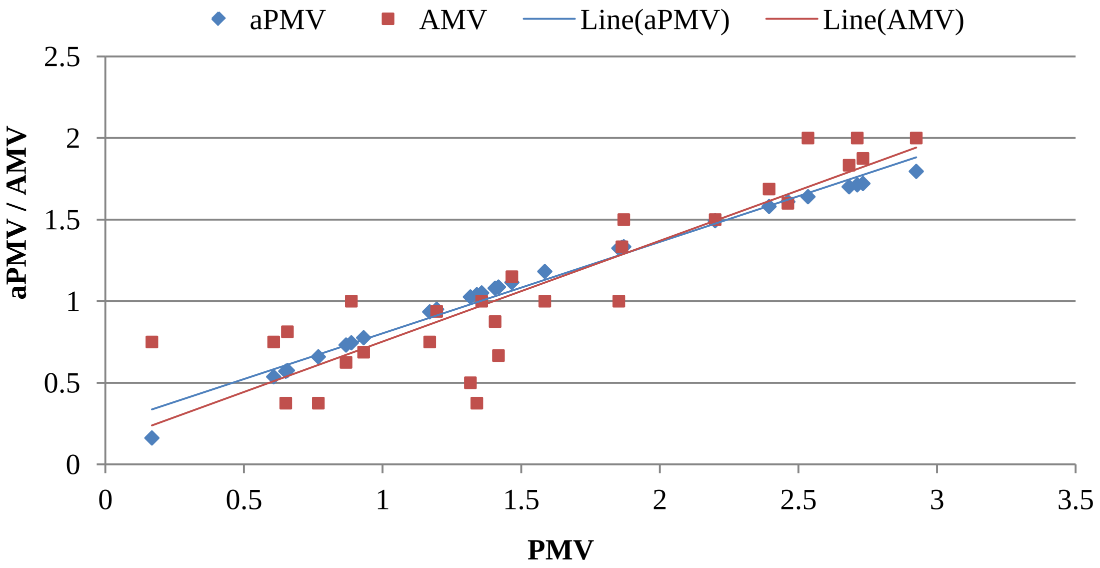


Figure4.12 The relationship between PMV, aPMV and AMV for hot summer conditions in case B

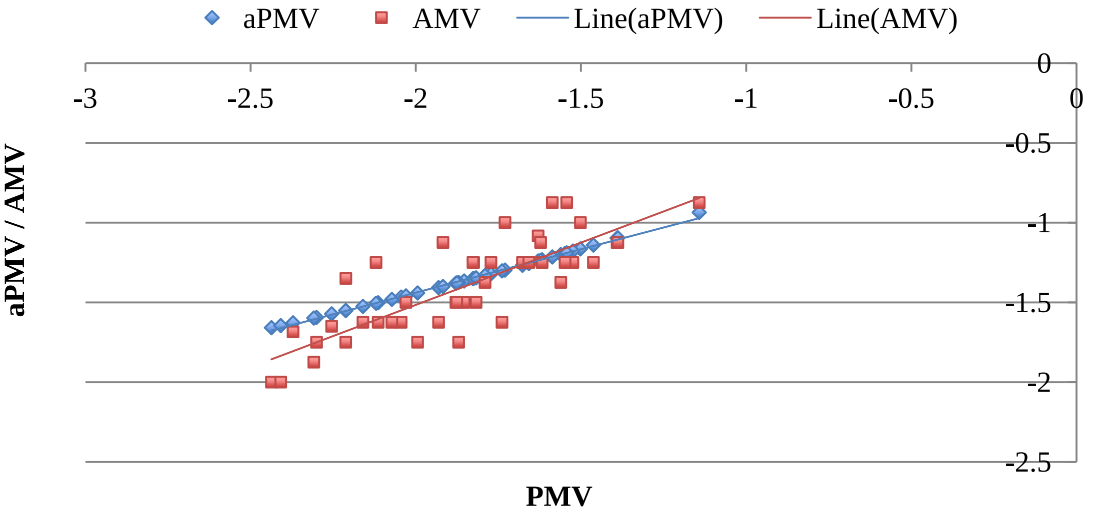


Figure4.13 The relationship between PMV, aPMV and AMV for cold winter conditions in case A

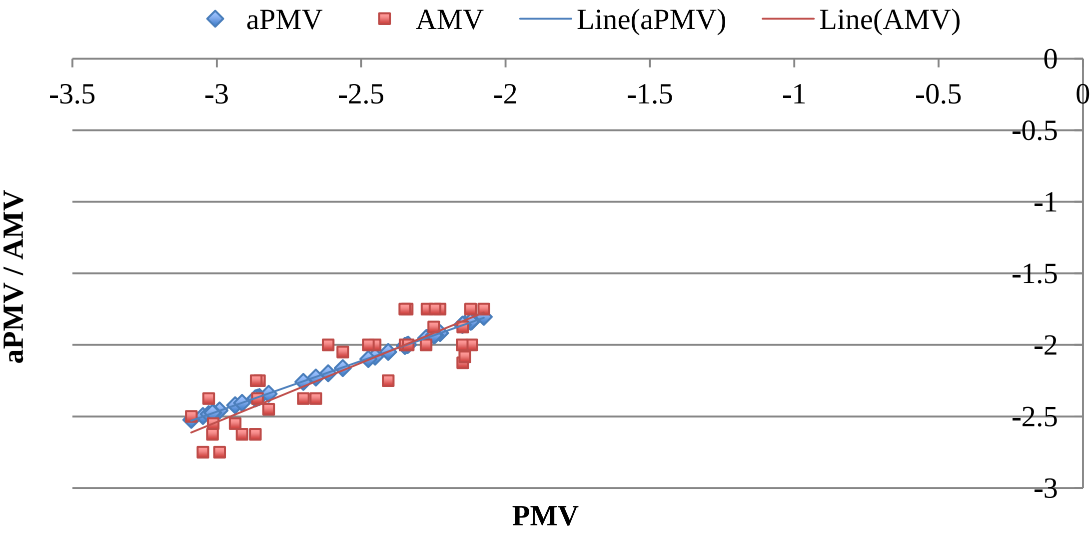


Figure4.14 The relationship between PMV, aPMV and AMV for cold winter conditions in case B

The comparative plots of votes (PMV, aPMV and AMV) for summer conditions in both cases are drawn in Figure4.11 and 12. The fit of aPMV and AMV is good for hot summer conditions and the deviation of aPMV model is smaller than that of the AMV calculations when compared with the PMV calculation. Figure4.13and 14 show the relationship of the thermal sensations votes (PMV, aPMV and AMV) during wintertime. It also has a good degree of linear regression, and aPMV model has less deviation of the data set. There are plenty of areas of the PMV model which are over the cold limit of -3, however, the corresponding values of the AMV and aPMV model are all included in the cold limit range from 0 to -3. These drawing plots provide validation of the adaptive coefficient for the extension study of the PMV model and aPMV model which make the AMV votes into more accurate values resulting in a regional regularisation presentation of actual occupants' thermal perspectives. The adaptive coefficient is a quantisation of the deviation of PMV and AMV under the same indoor environment. Adaptive mechanism is based on the different socio-cultural backgrounds of people, as well as their regional climatic culture and living habits. Moreover, the adaptive coefficient of unfixed factors result in different neutral indoor air temperatures with different thermal comfort ranges in different climatic zones, as reported by Singh et al.(Singh et al. 2011).

4.6.2 THE NEUTRAL TEMPERATURE AND THERMAL COMFORT RANGE

The field study focused on the duration of hot summer months (July and August) and cold winter months (December and January). By using the least square deviation method to calculate the regional adaptive coefficient λ of aPMV model of actual indoor thermal sensation vote, the aPMV values provide the occupants' thermal sensation whilst taking account of non-physiological factors (psychological and behavioural factors). Figure 4.15 represents the regression of aPMV on the indoor air temperature in both cases. By matching the seven-point ASHRAE thermal sensation scale, the neutral temperature in Yichang (before occupants start to use any mechanism of adaptation) is 21.4°C in case A and 22.6°C in case B. These findings are similar to those results from the field study on the Chongqing classroom developed by Yao et al.(R. Yao et al. 2010). If we suppose the acceptable thermal sensation range is between -1 and 1 based on the ASHRAE seven-point scale, the acceptable thermal sensation range according to the indoor air temperature scope is from 15.4°C to 27.4°C in case A, and from 16.8°C to 28.3°C for case B. These results imply that occupants in the prototype of case B have a higher tolerance to hot conditions than those of the prototype of case A. During the cold indoor conditions, occupants have a higher tolerance in case A to extremely low temperatures indoors than those of case B.

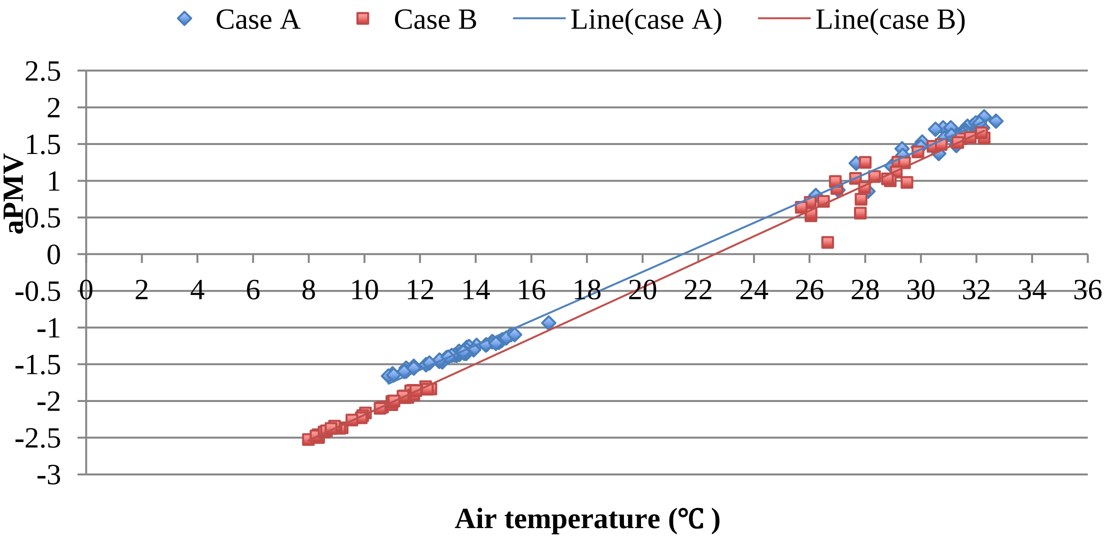


Figure4.15The regression of actual predicted mean vote (aPMV) on indoor air temperature in both case A and case B

$aPMV_A = 0.167T_{ia} - 3.578$ ($R^2 = 0.99$)--- (Equation4-21);

$aPMV_B = 0.174T_{ia} - 3.926$ ($R^2 = 0.95$) --- (Equation4-22);

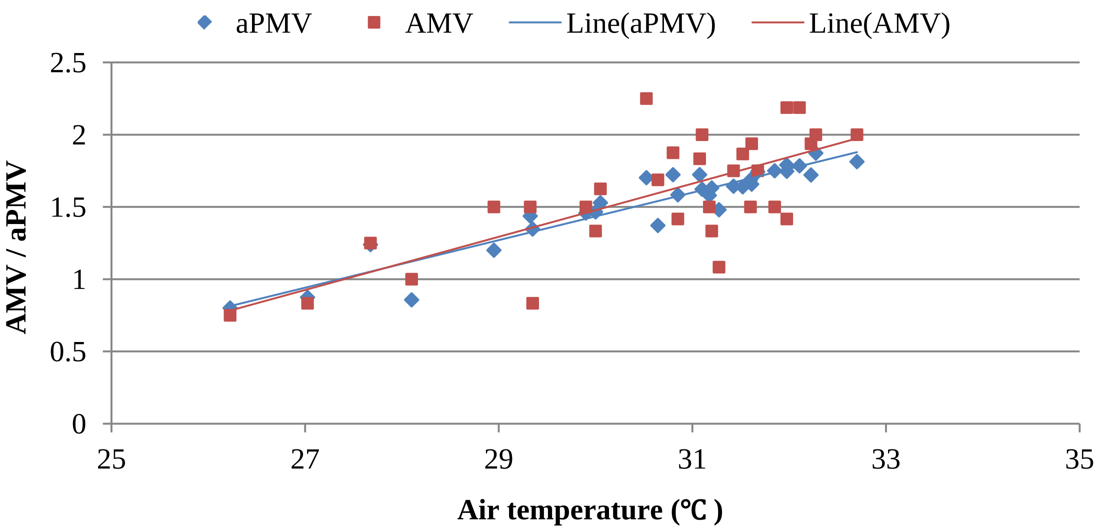


Figure4.16The relationship between aPMV model calculation results, AMV and indoor air temperature in case A in the hot summer in Yichang, China.

AMV = 0.184T$_{ia}$ - 4.044 ($R^2 = 0.527$)--- (Equation4-23);

aPMV = 0.164T$_{ia}$ - 3.499 ($R^2 = 0.879$)--- (Equation4-24);

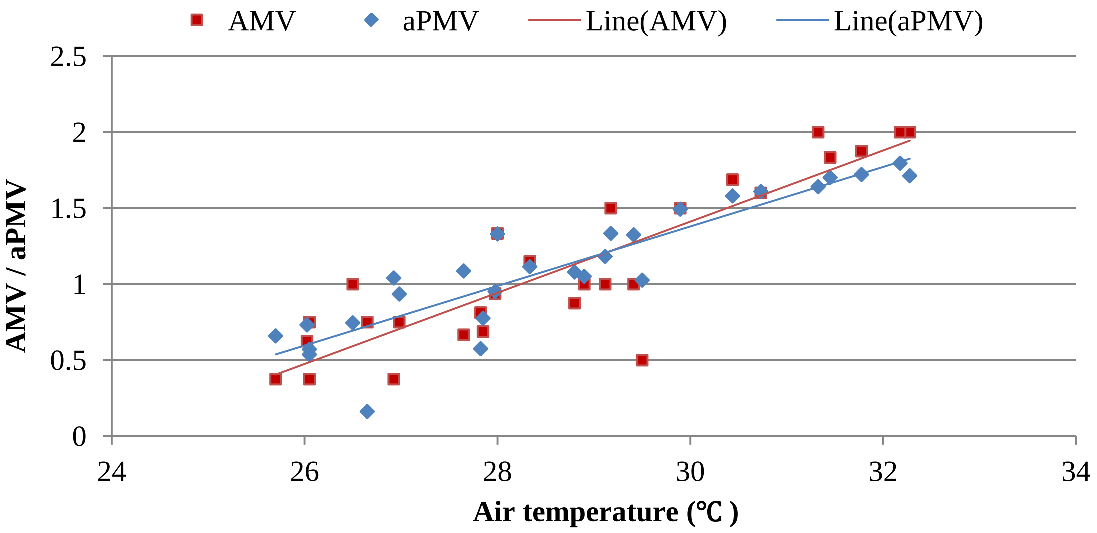


Figure4.17The relationship between aPMV model calculation results, AMV and indoor air temperature in case B in the hot summer in Yichang, China.

AMV = 0.234T$_{ia}$ - 5.612 ($R^2 = 0.776$)--- (Equation4-25);

aPMV = 0.195T$_{ia}$ - 4.496 ($R^2 = 0.817$)--- (Equation4-26);

Analysing the deviation between the aPMV model and the AMV model during a warm situation shows that if the indoor air temperature of case A is over 27.25 °C the AMV results would be higher than that of aPMV calculation, and the thermal sensation is nearly at 1.0 (slightly warm) of the ASHRAE seven-point scale. If the indoor air temperature of case B is over 28.62°C, the AMV results would be higher than that of aPMV calculation, and the thermal sensation is nearly at 1.0 (slightly warm) as well. In Figure4.16 and 17 the AMV model represents the different thermal sensitivity in the two different prototype cases. We can see that the slopes of the linear fit AMV equations (4-23) and (4-25) which are 0.184 unit/°C in case A and 0.234 unit/°C in case B, respectively. This indicates that thermal response based on the AMV model in case A is less sensitive than that of case B. Vice versa, the sensation scale alongside the temperature range of the AMV model in case A is 5.4 °C/unit, which is greater than that of the AMV in case B at 4.2°C/unit. For the aPMV model the slopes of equations (4-24) and (4-26) are 0.164unit/°C in case A and 0.195unit/°C case B for a hot situation. Therefore the reciprocal values are 6.1 °C/unit in case A and 5.1 °C/unit in case B respectively.

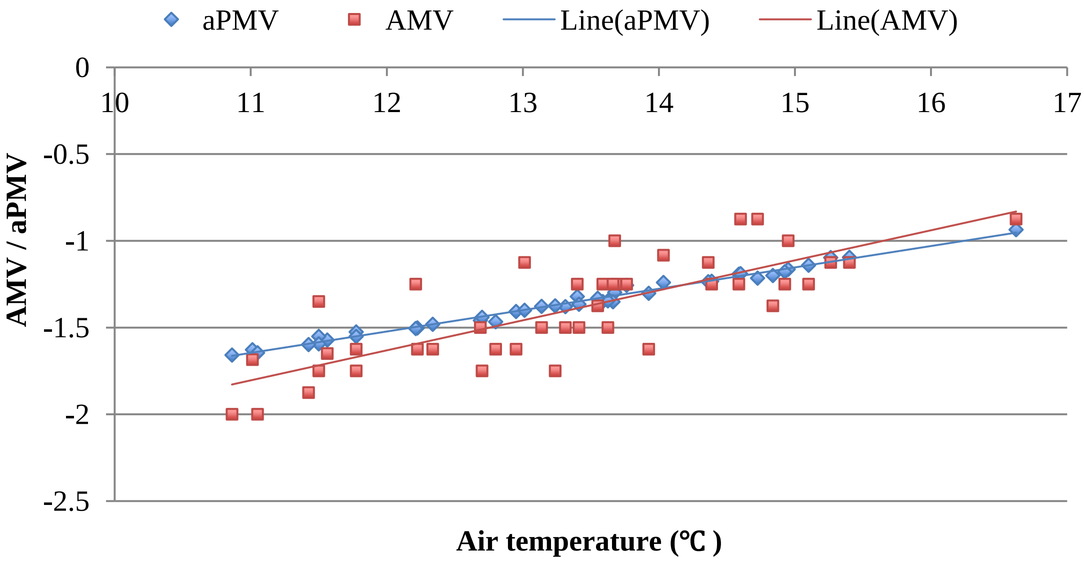


Figure4.18The relationship between aPMV model calculation results, AMV and indoor air temperature in case A in cold winter in Yichang, China.

AMV = $0.173T_{ia}$ - 3.707(R^2 = 0.630)--- (Equation4-27);

aPMV = $0.123T_{ia}$ - 3.001 (R^2 = 0.985)--- (Equation4-28);

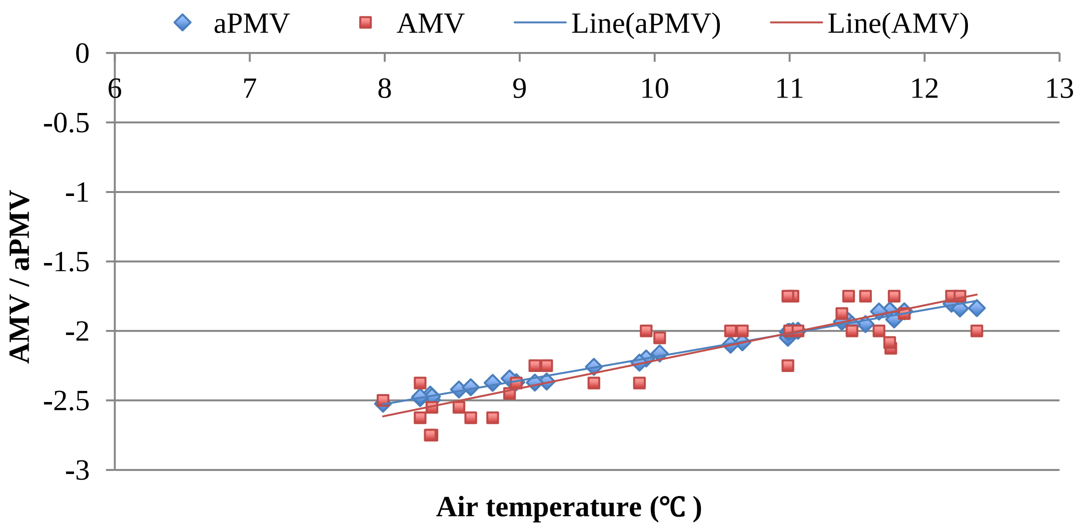


Figure4.19The relationship between aPMV model calculation results, AMV and indoor air temperature in case B in cold winter in Yichang, China.

AMV = $0.199T_{ia} - 4.204$ ($R^2 = 0.775$) --- (Equation4-29);

aPMV = $0.169T_{ia} - 3.881$ ($R^2 = 0.990$)--- (Equation4-30);

Analysing the deviation between the aPMV model and the AMV model during a cold situation shows that if the indoor air temperature of case A is over 14.12°C , the AMV results would be lower than that of aPMV calculation, and the thermal sensation is at nearly -1.3°C (cooler than ‘slightly cool’) on the ASHRAE seven-point scale. If the indoor air temperature of case B is over 10.77°C, the AMV results would be higher than that of aPMV calculation, and the thermal sensation is nearly at -2.0°C (cool). In Figure4.18 and 19, we can see that in winter time the slopes of the linear fit the AMV equations of (4-27) and (4-29) and are 0.173unit/°C in case A and 0.199 unit/°C in case B respectively. This indicates that the thermal response of the AMV model in case A is less sensitive than that of case B for cold conditions. Vice versa, looking at the sensation scale alongside the temperature range change of the AMV model in case A is 5.4 °C/unit, which is greater than that of the AMV in case B which has the value of 4.2°C/unit. For the aPMV model the slopes of equations (4-28) and (4-30) are 0.164unit/°C in case A and 0.195unit/°C in case B for hot situations. Therefore the reciprocal values are 6.1 °C/unit in case A and 5.1 °C/unit in case B respectively.

4.7 THE REGIONAL SUBJECTIVE THERMAL SENSATION SURVEY

As the former parts of this chapter have mentioned, the participants responded with their thermal sensation votes regarding hot summer and cold winter in the field study. We found that in the AMV records there existed quite a great discrepancy with the calculation results of PMV-PPD model. In hot summer the PMV provides a series of overestimated predictions, and underestimated values in cold winter. In other words the occupants staying in local residential buildings usually have subjective adaptive approaches that are based on physiological, psychological and behavioral adjustments for dealing with the discomfort. In this part of the field study the first thermal response is a subjective thermal sensation indicating the personal realization of a building's thermal environment, categorised by applying the ASHRAE seven-point scale, from the neutral point of just right (0) to hot orientation (3) and cold orientation (-3). The secondary thermal sensation index is the indoor thermal comfort (Oc) assessment, based on each warming or cooling sensation thermal perception vote. It is designed as a five-point scale from a comfortable feeling (0) to an absolutely uncomfortable sensation (4). The third index is the personal thermal tolerance (Tt), which is also designed as a five-point scale between values 0 (perfectly bearable) and 4 (absolutely unbearable). In this study the scale points of 0 and 1 (perfectly bearable and slightly difficult to bear) are defined as acceptable tolerance votes, whilst the scale points of 2, 3 and 4 are deemed to be unacceptable tolerance votes. As with the previous parts of the field study data collection, occupants giving their thermal sensation votes and personal thermal comfort judgment votes responded with different levels of thermal tolerance capacity. It is inferred that variant personal characteristics of thermal tolerance can produce differing perceptions of thermal sensations (cooling or warming) and uncomfortable conditions. This part of the research aims to investigate acceptable and unacceptable capacities in the two prototypes of case A and B.

Table 4.7 Personal acceptability of case A in hot summer AMV Cross-tabulation

			Actual Mean Vote (AMV)				**Total**
			0	**1**	**2**	**3**	
Personal acceptability	**Accep.**	**Count**	9	121	106	1	237
		% Accep.	3.8	51.1	44.7	0.4	100.0
		% AMV	100.0	87.7	53.0	5.6	64.9
		%Total	2.5	33.2	29.0	0.3	64.9
	Unaccep.	**Count**	0	17	94	17	128
		% Accep.	0.0	13.3	73.4	13.3	100.0
		% AMV	0.0	12.3	47.0	94.4	35.1
		% Total	0.0	4.7	25.8	4.7	35.1

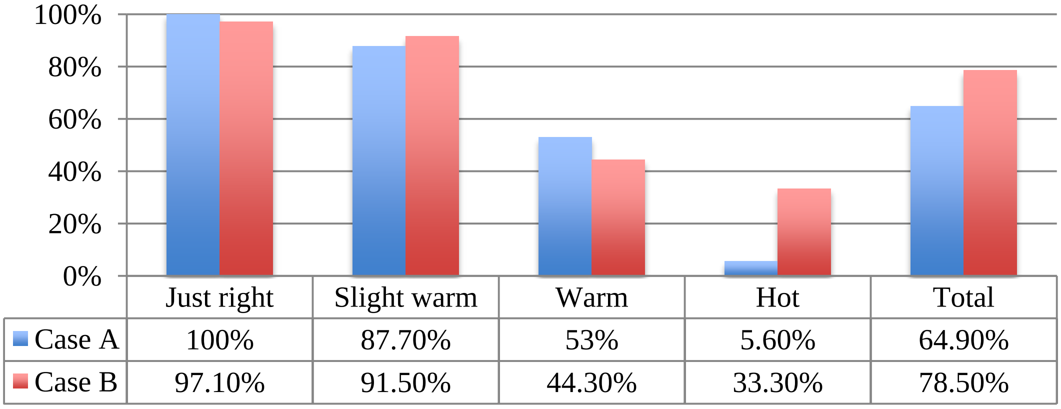
Total		**Count**	9	138	200	18	365
		% Accep.	2.5	37.8	54.8	4.9	100.0
		% AMV	100.0	100.0	100.0	100.0	100.0
		% Total	2.5	37.8	54.8	4.9	100.0

From Table 4.7 we can see that 64.9% of participants expressed their acceptance in the duration of the field study in hot summer, and 35.1% expressed their unacceptable assessment for the hot conditions. The tricky thing is that 49.1% of respondents voted their thermal sensation at level 2 (warm) and 3 (hot) in case A, but still presented an acceptable response for the thermal conditions that they were exposed to. Conversely, 11.6% of the respondents voted their thermal sensation at level 0 (just right) and 1 (slightly warm) in case A, yet still found the thermal conditions unacceptable. These results indicate that in hot summer quite a number of occupants stay in an indoor environment and have an acclimatized thermal tolerance. In other words, although occupants sense the warm conditions they can accept them in an appropriate range.

Table 4.8 Personal acceptability of case B in hot summer AMV Cross-tabulation

			Actual Mean Vote (AMV)				**Total**
			0	**1**	**2**	**3**	
Personal acceptability	**Accep.**	**Count**	66	172	43	3	284
		% Accep.	23.2	60.6	15.1	1.1	100.0
		% AMV	97.1	91.5	44.3	33.3	78.5
		% Total	18.2	47.5	11.9	0.8	78.5
	Unaccep.	**Count**	2	16	54	6	78
		% Accep.	2.6	20.5	69.2	7.7	100.0
		% AMV	2.9	8.5	55.7	66.7	21.5
		% Total	0.6	4.4	14.9	1.7	21.5
Total		**Count**	68	188	97	9	362
		% Accep.	18.8	51.9	26.8	2.5	100.0
		% AMV	100.0	100.0	100.0	100.0	100.0
		% Total	18.8	51.9	26.8	2.5	100.0

As the statistical analysis of the data collected in case B presented in Table 4.8 shows, 78.5% of respondents accepted the hot summer conditions, and 21.5% found them unacceptable. In the acceptable votes, 43.4% accept the warm (2) and hot (3) thermal conditions they occupy. 7.0% of participants did not accept warm acceptable conditions. Comparing the analysis results of cases A and B we find that there are differences in the acceptable percentages in each AMV survey in hot summer time. There is a higher acceptable percentage of 78.5% in case B than that the 64.9% registered in case A. Figure 4.20 shows that the acceptable percentage reduces with the gradually warmer indoor thermal sensation, and then the dissatisfaction sharply increases at the hot level in case A more than in case B. In general, there is more acceptability for warm situations in case B, and it has a remarkable degree of acceptability at very hot indoor occupancy.



	Just right	Slight warm	Warm	Hot	Total
🟦 Case A	100%	87.70%	53%	5.60%	64.90%
🟥 Case B	97.10%	91.50%	44.30%	33.30%	78.50%

Figure 4.20 The acceptability percentage of AMV in hot summer for case A and B

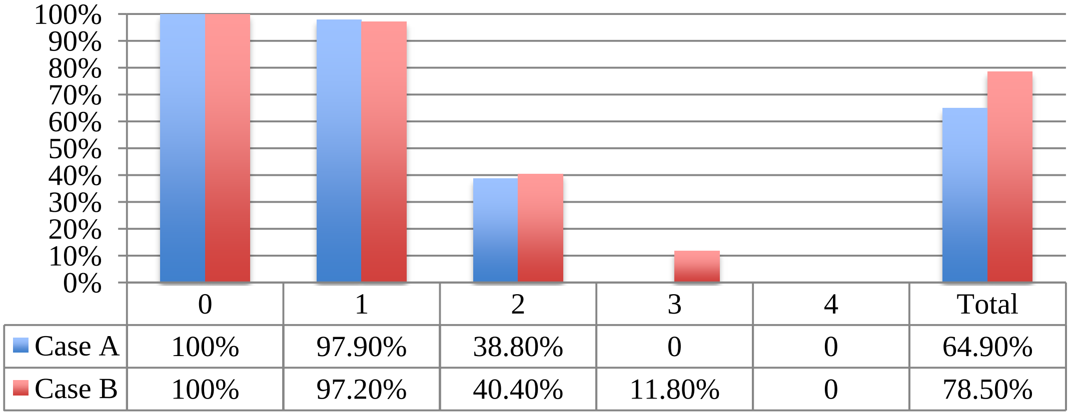
Table 4.9 Personal acceptability of case A in hot summer Overall comfort vote Cross-tabulation

			Overall comfort vote (Oc)					**Total**
			0	**1**	**2**	**3**	**4**	
Personal acceptability	**Accep.**	Count	44	143	50	0	0	237
		% Accep.	18.6	60.3	21.1	0.0	0.0	100.0
		% Oc	100.0	97.9	38.8	0.0	0.0	64.9
		% Total	12.1%	39.2	13.7	0.0	0.0	64.9
	Unaccep.	Count	0	3	79	45	1	128
		% Accep.	0.0	2.3	61.7	35.2	0.8	100.0
		% Oc	0.0	2.1	61.2	100.0	100.0	35.1
		% Total	0.0	0.8	21.6	12.3	0.3	35.1
Total		Count	44	146	129	45	1	365
		% Accep.	12.1	40.0	35.3	12.3%	0.3	100.0
		% Oc	100.0	100.0	100.0	100.0	100.0	100.0
		% Total	12.1	40.0	35.3	12.3	.3%	100.0

Table 4.10 Personal acceptability of case B in hot summer Overall comfort vote Cross-tabulation

			Overall comfort vote				**Total**
			0	**1**	**2**	**3**	
Personal acceptability	Accep.	Count	105	137	40	2	284
		% Accep.	37.0	48.2	14.1	0.7	100.0
		% Oc	100.0	97.2	40.4	11.8	78.5
		% Total	29.0	37.8	11.0	0.6	78.5
	Unaccep.	Count	0	4	59	15	78
		% Accep.	0.0	5.1	75.6	19.2	100.0
		% Oc	0.0	2.8	59.6	88.2	21.5
		% Total	0.0	1.1	16.3	4.1	21.5
Total		Count	105	141	99	17	362
		% Accep.	29.0	39.0	27.3	4.7	100.0
		% Oc	100.0	100.0	100.0	100.0	100.0
		% Total	29.0	39.0	27.3	4.7	100.0

The overall comfort vote is another kind of thermal environment description that is different from thermal sensation with its seven-point scale. This five-point scale vote can provide respondents' personal evaluation of their thermal comfort decision by referring to their own thermal sensation votes. The zero point means a comfortable vote, and I supposed that the level of slightly uncomfortable or below (0 level) is acceptable. Therefore the research aim is to find out the percentage of acceptability with the discomfort votes. From Table 4.9, there is a total of 64.9% acceptable votes and 35.1% unacceptable votes. In the discomfort range (2-4) of overall comfort votes there are 28.6% acceptable votes in case A, compared with 36.2% acceptable votes in case B. Only 1.6% of respondents voted dissatisfaction in the range of acceptable overall votes (0-1) in case A, and 2.7% in case B.



	0	1	2	3	4	Total
🟦 Case A	100%	97.90%	38.80%	0	0	64.90%
🟥 Case B	100%	97.20%	40.40%	11.80%	0	78.50%

Figure 4.21 The acceptability percentage of overall comfort in hot summer for cases A and B

According to the Figure 4.21, if the voting records fall into the range between 0 and 1, the acceptable percentage always remains at quite a high level of around 97% or 100%. This indicates the accuracy of the previous hypothesis, which supposed that levels 0 and 1 are in the acceptable range of residential building environments in the HSCW zone. The range of unacceptable discomfort levels (2-4) has proportionally lower acceptability and the percentage of acceptable votes in case B is higher than in case A.

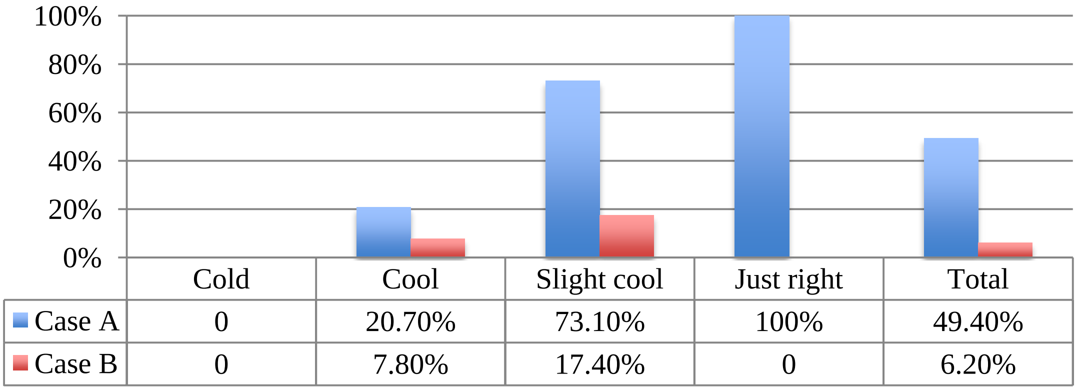
Table 4.11 Personal acceptability of case A in cold winter AMV Cross-tabulation

			Actual Mean Vote				**Total**
			-3	**-2**	**-1**	**0**	
Personal acceptability	**Accep.**	**Count**	0	34	122	18	174
		% Accep.	0.0	19.5	70.1	10.3	100.0
		% AMV	0.0	20.7	73.1	100.0	49.4
		% Total	0.0	9.7	34.7	5.1	49.4
	Unaccep.	**Count**	3	130	45	0	178
		% Accep.	1.7	73.0	25.3	0.0	100.0
		% AMV	100.0	79.3	26.9	0.0	50.6
		% Total	0.9	36.9	12.8	0.0	50.6
Total		**Count**	3	164	167	18	352
		% Accep.	0.9	46.6	47.4	5.1	100.0
		% AMV	100.0	100.0	100.0	100.0	100.0
		% Total	0.9	46.6	47.4	5.1	100.0

Table 4.12 Personal acceptability of case B in cold winter AMV Cross-tabulation

			Actual Mean Vote				**Total**
			-3	**-2**	**-1**	**0**	
Personal acceptability	Accep.	Count	0	14	4	0	18
		% Accep.	0.0	77.8	22.2	0.0	100.0
		% AMV	0.0	7.8	17.4	0.0	6.2
		% Total	0.0	4.8	1.4	0.0	6.2
	Unaccep.	Count	90	165	19	0	274
		% Accep.	32.8	60.2	6.9	0.0	100.0
		% AMV	100.0	92.2	82.6	0.0	93.8
		% Total	30.8	56.5	6.5	0.0	93.8
Total		Count	90	179	23	0	292
		% Accep.	30.8	61.3	7.9	0.0	100.0
		% AMV	100.0	100.0	100.0	0.0	100.0
		% Total	30.8	61.3	7.9	0.0	100.0

In the field study of cold winter presented for case A (see Table 4.11), 49.4% of respondents registered their acceptable attitude in the cool orientation of AMV in case A, and 50.6% voted for unacceptability. In the range below -1 (slight cool), 20.4% of participants can still accept the cold conditions in the voting range -2 and -3, and 24.3% voted ‘unacceptable’ for comfort range 0 and -1. As the summaries of Table 4.12 show, in case B only 6.2% of participants represented their acceptable attitude in the cool orientation of AMV votes, and 93.8% of respondents did not accept the cold conditions. For the AMV scale of cool and cold only 5.2% of people accept the cold conditions.



	Cold	Cool	Slight cool	Just right	Total
🟦 Case A	0	20.70%	73.10%	100%	49.40%
🟥 Case B	0	7.80%	17.40%	0	6.20%

Figure 4.22 The acceptability percentage of AMV in cold winter for case A and B

As demonstrated by the statistical analysis between thermal sensation votes and personal acceptable votes (see Figure 4.22), 49.4% of respondents accept the cold conditions in case A, but only 6.2% in case B. In case A 100% of respondents accept the neutral point of the thermal environment. When they felt the slight cool of the ambient thermal environment, 73.1% of respondents accept the cold conditions. When they felt the cool of the thermal environment 20.7% accept the cold conditions. For the case B field study there are lower percentages of people who accept the cold conditions in each level of thermal sensation (17.4% in slight cool and 7.8% in cool). Moreover there are no votes for just right (0) conditions.

According to the cross-tabulation between the overall thermal comfort vote and personal acceptability in Table 4.13, there is a total of 49.4% acceptable votes for the cold situations in case A. For the range of obvious discomfort from 2 to 4 in case A, 29.9% still felt that it is acceptable. 50.6% of respondents felt that the cold situations in case A were unacceptable, and for the range of 0 and 1 there is no unacceptable voting records in case A. As the presentation of Table 4.14 shows, in case B there is a total of 6.2% acceptable votes. For the range of obvious discomfort from 2 to 4 in case B, only 5.2% of respondents felt that it is acceptable. 93.8% of respondents felt that the cold situations are unacceptable, and there is no unacceptable voting records in case A for the overall comfort votes of 0 and 1.

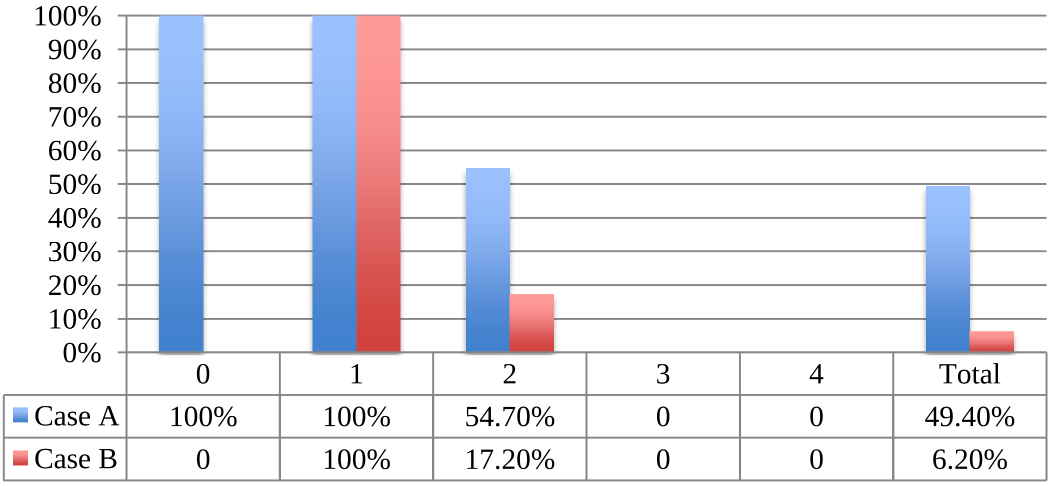
Table 4.13 Personal acceptability of case A in cold winter Overall comfort vote Cross-tabulation

			Overall comfort vote					**Total**
			0	**1**	**2**	**3**	**4**	
Personal acceptability	**Accep.**	**Count**	5	93	76	0	0	174
		% Accep.	2.9	53.4	43.7	0.0	0.0	100
		% Oc	100	100	54.7	0.0	0.0	49.4
		% Total	1.4	26.4	21.6	0.0	0.0	49.4
	Unaccep.	**Count**	0	0	63	114	1	178
		% Accep.	0.0	0.0	35.4	64.0	0.6	100
		% Oc	0.0	0.0	45.3	100.0	100	50.6
		% Total	0.0	0.0	17.9	32.4	0.3	50.6
Total		**Count**	5	93	139	114	1	352
		% Accep.	1.4	26.4	39.5	32.4	0.3	100
		% Oc	100	100	100	100.0	100	100
		% Total	1.4	26.4	39.5	32.4	0.3	100

Table 4.14 Personal acceptability of case B in cold winter Overall comfort vote Cross-tabulation

			Overall comfort vote					Total
			0	1	2	3	4	
Personal acceptability	Accep.	Count	0	3	15	0	0	18
		% Accep.	0.0	16.7	83.3	0.0	0.0	100
		% Oc	0.0	100	17.2	0.0	0.0	6.2
		% Total	0.0	1.0	5.1	0.0	0.0	6.2
	Unaccep.	Count	0	0	72	182	20	274
		% Accep.	0.0	0.0	26.3	66.4	7.3	100
		% Oc	0.0	0.0	82.8	100.0	100	93.8
		% Total	0.0	0.0	24.7	62.3	6.8	93.8
Total		Count	0	3	87	182	20	292
		% Accep.	0.0	1.0	29.8	62.3	6.8	100
		% Oc	0.0	100	100	100.0	100	100
		% Total	0.0	1.0	29.8	62.3	6.8	100

According to Figure 4.23, there are no overall thermal comfort votes for levels 3 and 4, which means that the occupants have tolerance to face the cold winter conditions. In the voting range of 0 to 1 the acceptable percentage reached a perfect 100%. It is indicated that the overall comfort levels 0 and 1 are realized to be in the acceptable range. In the range of unacceptable discomfort levels (2-4), there is a greater percentage of acceptable votes in case A than in case B. The result implied that at the same level of indoor uncomfortable conditions, occupants who participated in case A have nearly triple the thermal acceptability of their counterparts in case B.



	0	1	2	3	4	Total
🟦 Case A	100%	100%	54.70%	0	0	49.40%
🟥 Case B	0	100%	17.20%	0	0	6.20%

Figure 4.23 The acceptability percentage of overall comfort in cold winter for cases A and

4.8 CONCLUSIONS

According to the adaptive thermal comfort theory, the subjective people-participation has considerable impact for thermal comfort perception, and it is not a constant standard, depending on complex factors of regional climatic culture, as well as physiological and non-physiological factors (psychological and behaviour adaptation). The adaptive coefficient is an available and effective way to fill the gap between the rational thermal comfort model and field study in the real world. There are some conclusions listed below:

- Although the case study of the residential building is controlled by a split-type air conditioner along with natural ventilation, the overheating and overcooling potential still existed in both selected cases during the extreme seasons of the hot summer and cold winter.
- According to the field study data of AMV, subjective perception votes and PMV objective calculation, the directly subjective thermal perception preferences have relatively low levels of explanation by these regression equations of (4-8) (4-10) (4-12) (4-14) linked with air temperature. In both cases, according to the slope of each equation of thermal sensitivity response, the field studies indicate that the respondents can tolerate a wider indoor air temperature range by subjective perception under both hot and cold situations. The sensitivity ranges (hot and cold) in case B were usually higher than those of case A regardless of the AMV votes and PMV calculation. In this field study, respondents have higher sensitivity for hot situations than cold situations in both cases.

- As the adaptive coefficient calculation, it could be used as a reference of thermal comfort design for local residential buildings. The aPMV model analysis indicates that case A has a warmer sensation than case B in both the hot summer and cold winter.
- The field studies display that the neutral temperature in Yichang is 21.4°C in case A and 22.6°C in case B. The acceptable thermal sensation preference ranges from 15.4°C to 27.4°C in case A, to 16.8°C to 28.3°C in case B. The aPMV models have a higher correlation coefficient with a higher level of explanation than that of the AMV model. The aPMV model has relatively lower thermal sensitive results than that of AMV model and PMV model.
- Under hot summer weather situations, case B has more chance of subjective sensation for higher level in thermal acceptability than that in case A, especially in extreme situations of hot sensation and more than the level of very uncomfortable. The acceptability percentage reduces with the gradually warmer indoor thermal sensation, and then the dissatisfaction sharply increases at the hot level in case A more than in case B. In general, there is more acceptability for warm situations in case B, and it has a remarkable degree of acceptability at very hot indoor occupancy. On the contrary， case A has more chance of subjective acceptability than that in case B under cold winter weather situations. The result implied that at the same level of indoor uncomfortable conditions, occupants who participated in case A have nearly triple the thermal acceptability of their counterparts in case B.
- Applying an adaptive approach in this field study is a good addition for thermal comfort research, and it fills the gap between subjective thermal sensation and objective experimental calculation. It provides a practical solution for developing thermal-environment control and thermal-comfort assessment. In this research two case studies of typical residential buildings in China extend the research on adaptive thermal comfort, and investigate the thermal comfort in a mixed mode of building environment. This is very important for the future of residential building’s environmental design and is useful too for the parametric design of green building construction in HSCW zones in the future.

CHAPTER 5 OCCUPANTS’ SUBJECTIVE ADAPTATIVE PREFERENCE FOR THERMAL PERCEPTION IN RESIDENTIAL ENVIRONMENTS

5

5.1 INTRODUCTION

Based on research into adaptive thermal comfort, the occupants' thermal sensations take into account people's adaptive approaches for ambient discomfort from a building's indoor environment, especially the non-physiological adaptations. This includes psychological and behavioural adaptations which are similar to the physiological adaptations associated with a 'Black Box' for a complex process. This chapter is going to discuss the psychological adaptation and its related factors, which include morphological difference, socio-cultural background and building layout difference. The relationship of regression equations are summarised for acceptable thermal comfort ranges with upper and lower limits included. The psychological comfort boundary is linked with regional climatic data for common cognition equations explaining the relationship with monthly outdoor mean air temperatures. In this chapter, the field study also provides examples of regional attitudes towards thermal comfort and energy conservation. Section 5.2 presents the existing research of adaptive thermal comfort based on non-physiological factors. Section 5.3 gives a theoretical framework of psychological adaptation study. Section 5.4 presents the field study of questionnaire survey design. Section 5.5 is study results of threshold limit of acceptable thermal comfort field study. Section 5.6 gives study results of thermal environment controls survey. Section 5.7 displays a series of statistical analysis of subjective survey. Section 5.8 presents the cognition of thermal comfort and energy efficiency in a field study of China HSCW zone.

5.2 EXISTING ADAPTIVE THERMAL COMFORT RESEARCH

In today's world, energy saving and carbon reduction are two main issues facing our difficulty of successful economic development – energy shortages, environmental pollution, social investment and so on (TUBEEI 2007). All of these problems encourage research into energy efficiency, indoor thermal comfort and the thermal performance of buildings generally. In fact there is currently a great positive potential for research into the adaptive and reactive thermal comfort of the human body, which includes physiological factors and non-physiological factors (psychological and behavioural). The main principle of studies into adaptive thermal comfort is to explore the different reactions people have when some change in the thermal situation produces discomfort. This reaction tends to restore their thermal comfort (J. F. Nicol and Humphreys 2002a). Lots of researchers focus on developing adaptive thermal comfort models about free running buildings (Cena and de Dear 2001; P.O. Fanger and Toftum 2002; Indraganti 2010b; McCartney and Fergus Nicol 2002; J. Fergus Nicol et al. 1999; R. Yao et al. 2009; Yun and Steemers 2010), and in the future, this research aims to understand how people react through behavioural adaptation in different climatic conditions (Indraganti 2010a). The thermoregulatory mechanism usually has a strong interaction with the external physical stimuli. According to related research (Gail S. Brager and de Dear 1998b; Fergus Nicol et al. 2012; R. Yao et al. 2009), a person’s reaction to their environment is a type of adaptive reflection for improving indoor thermal comfort and reducing the sometimes challenging indoor environment. A survey of adaptive thermal comfort research in comprehensive regions (Barlow and Fiala 2007; J. Liu et al. 2012b; R. Yao et al. 2010) shows that passive and active adaptive approaches are very important strategies for buildings with low energy supplies. All adaptation methods would affect energy consumption levels and even living costs. The psychological adaptation research is important because currently there is a lack of in-depth research examining both the subjective thermal expectations for indoor thermal comfort and the regional context of climatic conditions, which also need to be linked with psychological adaptation mechanisms. The subjective psychological effect is usually defined as referring to those other environment adaptation triggers of non-physiological factors which influence behavioural thermoregulatory mechanisms (Djongyang et al. 2010; Singh et al. 2011; R. Yao et al. 2009).

Reviewing the adaptive thermal comfort theory, all adaptation mechanisms are represented in lots of field studies researching behavioural reactions for reducing discomfort in an ambient physical environment. However, behavioural adaptation could hardly be handled in the reality of subjective occupancy, and it does not indicate the actual thermal comfort expectation and is easily disturbed by subjective issues. For instance, '*…occupants see environmental control measures to satisfy their thermal comfort requirements as much as they can…*' (J. Liu et al. 2012b). The behavioural sensitivity and decision strategies of an individual are all based on personal traits, social and cultural backgrounds, and the thermal expectations of psychological adaptation formed by all of them. As the research developed by de Dear demonstrates, psychological adaptation of self-regulation plays an important role for determining a human's thermal sensations (R. J. de Dear and Brager 1998). It is a complicated dynamic process based on the subjective experience of thermal perception, and is difficult to measure directly (R. J. de Dear and Brager 2002). The psychological adaptation of thermal comfort usually has a strong relationship with a person's age, sexual characteristics and a series of socio-cultural factors, therefore, we could investigate some typological factors to find out about the relationship between thermal comfort demand and subjective information.

5.3 THEORETICAL FRAMEWORK OF PSYCHOLOGICAL ADAPTATION

Psychological adaptation is one of non-physiological adaptation and is linked with behavioural adaptation by human beings. This is an extension of environmental psychological research on thermal environment satisfaction. Judgments and actions about one's environment are decided unconsciously, based on a psychological thermoregulator. The relationship between variables and the environment is complex, and all the psychological adaptations used for thermal comfort are controlled by a neurological response caused by a person's ability to sense an ambient thermal environment. There is a comfort limit of indoor air temperature and this is the most direct way to remind an occupant if they need to use behavioral adaptation to achieve comfort in a passive or mechanical way. Psychological adaptation could make people underestimate or overestimate the thermal environment change with their thermal sensation alteration. There are some related studies concerning the effects of psychological adaptation on the thermal environment in urban areas (Nikolopoulou and Steemers 2003), which provide a series of factors to describe a person's thermal response in a city space. It is found that the human being's perception of ambient urban space does not directly link with the magnitude of physical stimulus in the environment. That complicated process depends on the 'information' that people have for a particular situation. Psychological factors are presented in the following figures.

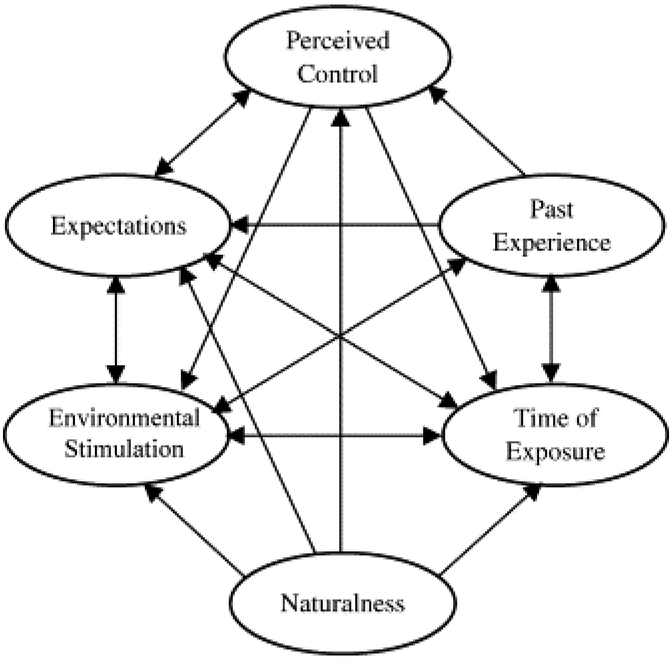


Figure 5.1 Lines of influence between different parameters of psychological adaptation

Figure 5.1 depicts the relationship between variant parameters of the psychological adaptation for thermal comfort based on the research of Nikolopoulou et al. The lines of influence have no weight and no magnitude on their relationship between each pair of parameters. Some links flow in a single direction and some influences are examples of a two-way relationship, for example "naturalness" has three single directions of influence on environmental stimulation, expectation and perceived control, and there is a two-way influence between expectation and perceived control. It is interesting to mention that 'naturalness' has been regarded as a parameter to influence other variables, but there is no any other parameters of the group have direct or indirect relationship. It seems that it is an inherent variable to environment. As we know, ''naturalness' make us a natural setting of characteristics preferred in an environment. It extends through a physical research to a social science scenic value. The scenic value is worth to be investigated for thermal comfort study and environmental psychological health, however it is hard to be scaled and categorized.

This psychological adaptation research listed the input-output influences of each parameter to demonstrate their interactions with one another in Figure 5.1. Table 5. 1 gives a further illustration of the links showing the different levels of relationship between variant parameters. Figure 5.2 indicates the degrees that parameters' influence, and are influenced, by another, grouping the different degrees of parameter from least to most (0-5). There are three parameters (time of exposure, environmental stimulation and expectation) in the most influential group of parameters. This wider notion of 'thermal comfort' quantified the speculative interrelationships for open space, and would also be referred to for indoor built environments.

Table 5. 1 Speculative interaction of different parameters of psychological adaptation

Speculative interaction of different parameters of psychological adaptation		
Parameter	**Influencing parameter**	**Being influenced by parameter**
Perceived control	3	3
Expectations	3	5
Environmental stimulation	3	5
Past experience	4	2
Time of exposure	3	5
Naturalness	4	0

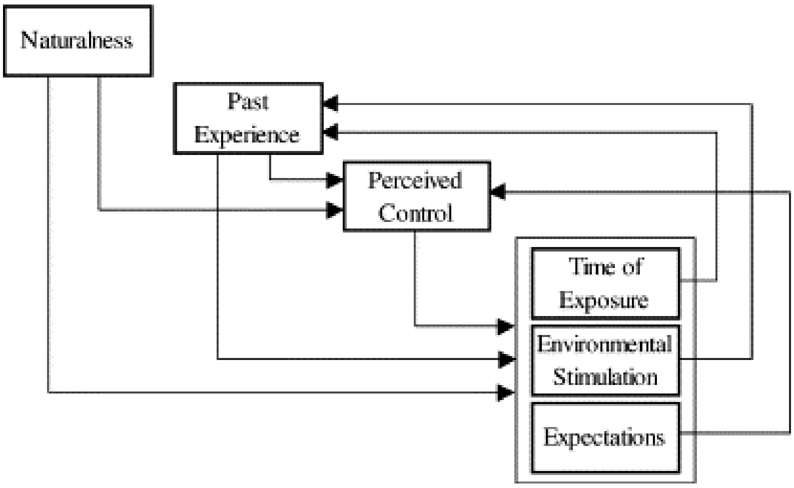


Figure 5.2 Network demonstrating interrelationships between the different parameters of psychological adaptation

These previous research findings have implications for the study of psychological adaptation and environmental thermal comfort as '...*this implies that the relationships between those variables are complex, as it is not a simple cause and effect situation. Satisfaction with the thermal environment of the space will depend as much on the space itself, as it will on personal variables people bring to the area with them, and the former will affect the latter, whereas, the latter will affect the perception of the former…*'(Nikolopoulou and Steemers 2003). We can find that research into psychological adaptation is a useful supplement to help match thermal comfort with real, physical environments. This thermal experience accumulation forms a personal cognition. The detailed research for this subjective empirical model could increase effective energy use and satisfy the indoor thermal comfort demand based on a suitable set-point indoor air temperature.

5.4 QUESTIONNAIRE SURVEY DESIGN

Based on the literature review of Auliciems' research (Auliciems 1981b) and a series of related knowledge, the altered perception, reaction and sensory information are all caused by subjective past thermal experience (Fergus Nicol et al. 2012; Race et al. 2010). Therefore, the questionnaire survey is not just designed for the data collection of a single point in time, but instead, is able to collect data over a period of time with a multiple-recording method to produce relatively stable test results. The records were taken over one week, every other day, three times in a day. The empirical data provides an average value of the threshold limit for each person's preferred acceptable comfort range. The survey was undertaken in two residential communities built for local middle class citizens in Yichang. In total, there are 262 respondents who participated in this field study. The questionnaire survey is designed to take periodical results, and so the survey was taken in the middle month of each season (there are two typical extreme seasons and two transition seasons). Typical extreme seasons include summer (June, July and

August) and winter (December, January and February), and transition seasons include spring (March, April and May) and autumn (September, October and November).

There are two typical Chinese apartments selected for the thermal environment study. One is a prototype of Y-axis layout (the main opening is on the narrow facade and the long depth of a Y-axis corridor) and the other one is an X-axis layout (the main opening is on the wide facade and has a square layout of an X-axis corridor). Although there is no empirical evidence to prove that psychological adaptations of indoor thermal comfort is affected by residential housing layout, related research suggests that the indoor layout design could influence a building’s thermal performance and energy consumption levels.

The first part of the questionnaire survey concentrates on r respondents’ anthropological information (age and gender), socio-cultural background (education level, job style and living experience), the testing environmental case, and the testing season. The respondents were randomly separated into two selected cases in each season.

The secondary part of the survey concerns the thermal environment control of indoor spaces (living room and main bedroom) in two selected cases and three sub-points have been involved in this section also. The first point considers the seasonal selection strategy of the choice of heating or cooling devices, and the preference of choice. The second point concerns the local energy efficiency ratio or coefficient performance ratio (EER or COP) for air-conditioning (AC) use. The indoor environments are controlled by individual air-conditioners which operate a cooling mode in summer and a heating mode in winter. They are assisted with an electrical cooling fan or heater for adjustment. The third point concerns the seasonal threshold limit of the indoor air temperature, examining temperatures of acceptable thermal comfort.

The third section of the survey is designed to test the regional attitude towards thermal comfort and energy saving. The culture of the regional thermal environmental has a strong link with the psychological suggestion of thermal sensation preference. These expected preferences decide how the personal thermal comfort adjustment mechanism will react and will even affect occupants’ energy consumption through equipment used for heating or cooling. The results could provide a clear indication of specific regional characteristics for facing the problem between the two polar issues of achieving thermal comfort whilst saving energy. The effective factors of energy use and thermal comfort are also involved in this part of survey, and the trends in the altering process during real seasons are investigated. The survey is designed with a nine-point range which considers two orientations of cognition (absolute thermal comfort or absolute energy saving). The extreme attitude towards absolute energy saving is defined at negative 4, with positive 4 representing an attitude at the opposite pole of absolute thermal comfort. The zero point represents a neutral attitude between the two poles. Negative or positive 2, respectively, refers to an occupants’ attitude which places particular stress on energy saving or thermal comfort. Negative or positive 1 and 3 stand for the middle value between 0 and 2 or 2 and 4 of personal preference.

This field study runs for the duration of one week and adequately considers that each independent sample has their own thermal experience. This makes the voting results close to the real average of the participants’ seasonal thermal expectation. The detailed process is designed to be taken at one-day intervals and there are three tests each day measuring the threshold limit of the acceptable thermal comfort temperatures (before occupants make use of any temperature adjustment mechanisms). The average values are calculated and recorded for one week in each season, and the survey was finished in the middle month of the season to guarantee an equal climatic stimulus for variant participants. The participants were taught to record their threshold limit of indoor air temperatures according to the temperature at which they decide to turn on the heating or cooling device for restoring thermal comfort. To ensure participants had a rich understanding of the research, there is a one day preliminary training session for each respondent and nearly all field studies can be finished in a couple of weeks within the same month.

5.5 THE THRESHOLD LIMIT OF ACCEPTABLE THERMAL COMFORT

Regarding actual data collection, there are 218 participants involved in the four seasonal tests and completion of questionnaires which resulted in a collection of 5936 datasets in total. Nearly all (92%) the participants are selected from the apartment of the two residential prototypes and 100% live in these two residential communities. According to their feedback, it is found that the threshold limit of indoor air temperatures are variant in different seasons, though the record of preferences of living room and bedroom temperatures did not show significant differences. The seasonal deviation exists because of fluctuations in the corresponding occupants' thermal experiences. The hot summer and cold winter have relatively higher and lower threshold limits of air temperature respectively. The extreme seasonal climate has a relatively narrow band of threshold limit variation and transition seasons have a relatively wider range. The descriptive statistical details are summarised in Table 5.2 for the four seasons. We can find that the seasonal thermal expectation preference has significant differences in a HSCW zone depending on the seasonal climate situations. In each season, the average values of 'living room' data did not have a significant difference from that collected from 'bedroom' data. That means occupants have a similar cognitional diversity of psychological experience for indoor thermal environment sensation.

Table 5.2 Summary of seasonal threshold limit of indoor air temperature records

Season threshold limit	**Spring**		**Summer**		**Autumn**		**Winter**	
	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
Valid N.	57	57	61	61	44	44	56	56
Mean	21.98	22.40	25.90	25.85	23.43	23.52	19.80	19.91
Std. dev	2.33	2.03	1.67	1.70	1.76	1.80	1.77	1.86
Range	9	8	6	6	7	7	6	6
Minimum	16.00	18.00	23.00	23.00	20.00	20.00	17.00	17.00
Maximum	25.00	25.00	29.00	29.00	27.00	27.00	23.00	23.00
Sig. (T_1-T_2)	No (0.346)		No (0.774)		No (0.907)		No (0.549)	

1- Living room
2- Bedroom

5.6 INVESTIGATION OF THERMAL ENVIRONMENT CONTROL STATUS

The adjustment mechanisms in residential buildings are mainly affected by the building operation and controls. The records are based on 97 valid respondents' reports collected from the prototype of case A, and 121 valid respondents' reports collected from the prototype of case B. The air-conditioner (AC) is the main mechanism for indoor thermal environment control accounting for over 95%. AC is not the only device for thermal adjustment in China's residential buildings in HSCW zones. There are some auxiliary mechanisms for thermal comfort restoration, for example, electric heaters (Abbazadeh et al.), under-floor heating (FH), and hot-water radiators are frequently used. For cooling, electric coolers and various fans are common place in hot summer.

There are a multiple choice of facilities for adjusting indoor heating and cooling to an acceptable level. AC is the most common mechanism for thermal control but it is not the first choice; people usually use some passive way to alter their comfort, for example opening a window, drinking cool or hot water, using a paper fan or some other small power device, and then gradually decide to use the major heating or cooling facilities. In the living rooms of participants in case A, about 60% voted an electric heater as their first choice for indoor heating and a fan as the first choice for cooling. No one chose AC as their first choice, although half of respondents chose AC as their second choice of cooling device. The first choice for heating in the bedrooms of participants of case A was AC (85%) and nearly half of them would use an electric heater for some special thermal preference. The first choice of cooling device was a fan (close to 67%) and AC was the second choice (about 65%). For participants of case B, the living room heating preference was EH with about 67% choosing this as their first choice. The second choice was AC with nearly 60% of votes. For the living room, the cooling preference for participants in case B was a fan (85%) and nearly 75% of respondents choose AC as their second choice. In the bedroom, participants of case B selected AC as the first choice for heating (nearly 85%) and EH as their second choice (nearly 60%). The first choice for cooling was using a fan (nearly 70%) and the second choice was AC (nearly 80%). The mechanism adjustment for thermal comfort is a positive way of behavioral adaptation based on the psychological upper or lower tolerance limit. These threshold values of acceptable thermal comfort range are based on personal thermal expectation, and are derived from their short-term thermal experience and long-term personal background. The information gathered from the regional background pattern research and short-term thermal experience data collection could help to encourage energy consumption in an intelligent way.

Table 5.3 Summary of indoor thermal control equipment and choice

Case A			**Living room**				**Bedroom**			
Samples			**Heating**		**Cooling**		**Heating**		**Cooling**	
Spring	22	97	AC	93.8%(91)	AC	97.9%(95)	AC	95.9%(93)	AC	95.9%(93)
Summer	27		EH	58.8%(57)	EC	28.9%(28)	EH	48.5%(47)	EC	17.5%(17)
Autumn	22		FH	4.1%(4)	Fan	76.3%(74)	FH	6.2%(6)	Fan	69.1%(67)
Winter	26		HWR	6.2%(6)			HWR	10.3%(10)		
First Choice			EH 58.8%(57)		Fan 62.9%(61)		AC 85.6% (83)		Fan 67.0%(65)	
Second Choice			AC 63.9% (62)		AC 52.6% (51)		EH 48.5% (47)		AC 64.9% (63)	

Case B			**Living room**				**Bedroom**			
Samples			**Heating**		**Cooling**		**Heating**		**Cooling**	
Spring	35	121	AC	96.7%(117)	AC	90.1%(109)	AC	86.8%(105)	AC	92.6%(112)
Summer	34		EH	63.6%(77)	EC	55.4%(67)	EH	69.4%(84)	EC	17.4%(21)
Autumn	22		FH	5.0%(6)	Fan	88.4%(107)	FH	2.5%(3)	Fan	76.0%(92)
Winter	30		HWR	5.8%(7)			HWR	5.0%(6)		
First Choice			EH 66.9% (81)		Fan 83.5% (101)		AC 84.3% (102)		Fan 71.1% (86)	
Second Choice			AC 59.5% (72)		AC 75.2% (91)		EH 58.7% (71)		AC 83.5% (101)	

5.7 THE STATISTICAL ANALYSIS OF SUBJECTIVE SURVEY

There are six parameters involved in this study of psychological research, two points of anthropological information (age and gender), three points of social background information (urban life, job and education) and a residential experience factor. All the questionnaire data is analysed using the software of ‘Statistic Package for Social Science’ (SPSS).

5.7.1 ANTHROPOLOGICAL FACTORS SURVEY

Table 5.4 lists the groupings specific to participants' age and gender. The survey roughly consisted of half younger participants (below 40 years old) and half older participants group (equal to, and above, 40 years old), and all respondents' age was lower than 60-years old (because of a special environment request due to health protection). With the exception of autumn, almost three quarters of the participants (72%) are younger people in this field survey. In terms of gender, there was an almost equal amount of males and females. Table 5.5 and Table 5.6 present the results of a two-tailed t-test that is used to compare the mean values of the threshold limit of indoor air temperature for different age and gender groups surveyed, for both living room and bedroom spaces. For the four seasons surveyed, all groups have significant differences and the highlighted sections (in red) means the Sig. value is lower than the cut-off of 0.05.

Table 5.4 Participant's age and gender grouping

Season	**Group**	**Spring**	**Summer**	**Autumn**	**Winter**
Age G.	<40	28	33	32	31
	Percentage	49.1%	54.1%	72.7%	55.4%
	>40	29	28	12	25
	Percentage	50.9%	45.9%	27.3%	44.6%
Gender	Male	24	31	27	25
	Percentage	42.1%	50.8%	61.4%	44.6%
	Female	33	30	17	31
	Percentage	57.9%	49.2%	38.6%	55.4%
Total		57	61	44	56
Percentage		100%	100%	100%	100%

Two groups' mean values are significantly different to one another, with the difference between mean values at about 3.5 °C in transitional seasons (spring and autumn) and about 2.5°C in extreme seasons (summer and winter). The group of older people always has a higher threshold limit of acceptable indoor air temperature. They have a higher thermal tolerance capacity against overheating in an indoor environment without needing to use an adjustment mechanism in comparison to the younger group. This is not the case during winter, by contrast. The data fluctuation range stands for the individual differences of thermal comfort preference, and the results show that the younger group has the narrowest range in the extreme season of hot summer and has the widest range in spring. The older group only has the narrowest range during autumn. This means, generally speaking, younger participants have a higher tolerance capacity for cold situations, and the older group has more endurance in summer time. We can find that in spring, which has seasonal cold spells before warming up slowly, the older group has more stable options of mental judgment than that of the younger group, who have a more diverse range of psychological decisions. This same phenomenon happens in the other transition season of autumn which has a hot spell before gradually cooling down. Both groups have a similar changing range during extreme seasons, thus hot summer has a higher rate of stable mental judgment than winter. There is no big difference between living room and bedroom space in this data analysis.

Table 5.5 Two-tailed t-test results of anthropological information in living room space

Living room		**Min.**	**Max.**	**Std. Devi.**	**Mean**	**Range**	**Sig.**
Spring	Below 40	16.00	25.00	2.15	20.39	9	Yes(0.000)
	Above 40	21.00	25.00	1.18	23.54	4	
	Male	18.00	23.00	1.50	20.58	5	Yes(0.000)
	Female	16.00	25.00	2.30	23.00	9	
Summer	Below 40	23.00	26.00	0.82	24.67	3	Yes(0.000)
	Above 40	25.00	29.00	1.16	27.36	4	
	Male	23.00	28.00	1.27	25.00	5	Yes(0.000)
	Female	24.00	29.00	1.53	26.83	5	
Autumn	Below 40	20.00	25.00	1.19	22.59	5	Yes(0.000)
	Above 40	25.00	27.00	0.78	25.67	2	
	Male	22.00	27.00	1.61	22.74	7	Yes(0.000)
	Female	22.00	27.00	1.42	24.53	5	
Winter	Below 40	17.00	22.00	1.26	18.74	5	Yes(0.000)
	Above 40	18.00	23.00	1.39	21.12	5	
	Male	17.00	21.00	1.08	18.40	4	Yes(0.026)
	Female	18.00	23.00	1.37	20.94	5	

As the result of the gender analysis shows, females always like a warmer environment than males whether in hot summer or cold winter. The difference in preference is about 2.5℃ between males and females in winter and spring, which is higher than that of 1.8℃. This indicates that the gender gap when examining the threshold limit of acceptable thermal comfort is larger in cold situations and smaller in warm situations. According to the difference of fluctuation ranges, we can find that a larger difference is present in the female group during spring, and for the male group a large difference occurred during autumn. However, the extreme seasons of summer and winter have an approximately equal difference between the male and female groups. It is indicated that the male group has more stable options of mental judgment than that of the female group through spring. In autumn, the male group has a more diverse range of psychological decisions. There is no significant difference when examining results about bedroom space.

Table 5.6 Two-tailed t-test results of anthropological information in bedroom space

Bedroom		**Min.**	**Max.**	**Std. Devi.**	**Mean**	**Range**	**Sig.**
Spring	**Below 40**	18.00	25.00	1.87	21.00	7	Yes(0.000)
	Above 40	22.00	26.00	1.02	23.76	4	
	Male	18.00	24.00	1.44	21.08	6	Yes(0.000)
	Female	18.00	26.00	1.87	23.36	8	
Summer	**Below 40**	23.00	27.00	1.05	24.67	4	Yes(0.000)
	Above 40	25.00	29.00	1.18	27.25	4	
	Male	23.00	28.00	1.40	24.97	5	Yes(0.000)
	Female	24.00	29.00	1.50	26.77	5	
Autumn	**Below 40**	20.00	25.00	1.26	22.69	5	Yes(0.000)
	Above 40	25.00	27.00	0.87	25.75	2	
	Male	20.00	27.00	1.63	22.78	7	Yes(0.000)
	Female	22.00	27.00	1.40	24.71	5	
Winter	**Below 40**	17.00	22.00	1.29	18.74	5	Yes(0.000)
	Above 40	18.00	23.00	1.38	21.36	5	
	Male	17.00	21.00	1.26	18.48	4	Yes(0.016)
	Female	18.00	23.00	1.41	21.06	5	

5.7.2 SOCIO-CULTUREAL BACKGROUND SURVEY

There are three points of socio-cultural background factor listed Table 5.7: the participants' urban living experience (there are two types of urban habitants: those who have lived in the city for a major percentage of their lives, i.e. half of their lifetime or more, and those who have moved to an urban area but have spent significant periods of their life outside of the city); job style (manual working, mixed work and mental style); and their education level (classified levels of low, middle and high). According to the table data, most of interviewees spent their lifetime in an urban area, with over 80% of participants in this group. Consequently, this field study is indicative of those people whose lives are dominated by urban living experiences. Regarding job style, the percentage of the people who have a mixed job style is approximately 50% of the total survey sample. The cerebral work group accounts for 30% which is higher than the manual working group which makes up 20% of the sample. Concerning participants' education level, the group with a 'middle' level of education was the largest, reaching 50-55%. The high-level group is roughly equal to that of the low-level group, at around 25%.

Table 5.7 Summary of the participant's urban living experience, job style and education level

Season	Group	Spring	Summer	Autumn	Winter
Urban	**Non-urban**	3	4	9	11
	Percentage	5.3%	6.6%	20.5%	19.6%
	Urban	54	57	35	45
	Percentage	94.7%	93.4%	79.5%	80.4%
Job	**Manual**	11	11	5	16
	Percentage	19.3%	18.0%	11.4%	28.6%
	Mixed	30	35	27	23
	Percentage	52.6%	57.4%	61.3%	41.1%
	Mental	16	15	12	17
	Percentage	28.1%	24.6%	27.3%	30.3%
Education	**Low**	13	15	11	17
	Percentage	22.8%	24.6%	25.0%	30.3%
	Middle	31	32	24	31
	Percentage	54.4%	52.4%	54.5%	55.4%
	High	13	14	9	8
	Percentage	22.8%	23.0%	24.5%	14.3%
Total		57	61	44	56
Percentage		100%	100%	100%	100%

Table 5.8 Two-tailed t-test and one-way ANOVA t-test for socio-cultural background in living room space

Living room		Min.	Max.	Std. Devi.	Mean	Range	Sig.
Spring	**Urban**	16.00	25.00	2.35	21.89	9	No(0.200)
	Non-urban	23.00	24.00	0.577	23.67	1	
	Manual job	20.00	24.00	2.02	21.91	4	No(0.729)
	Mixed job	16.00	25.00	2.62	22.20	9	
	Mental job	18.00	25.00	2.00	21.63	7	
	Low ed.	16.00	22.00	1.96	19.77	6	Yes(0.000)
	Middle ed.	18.00	25.00	2.02	22.32	7	
	High ed.	20.00	25.00	1.92	23.38	5	
Summer	**Urban**	23.00	29.00	1.68	25.84	6	No(0.297)
	Non-urban	25.00	28.00	1.5	26.75	3	
	Manual job	24.00	29.00	1.40	26.82	5	No(0.092)
	Mixed job	23.00	29.00	1.77	25.83	6	
	Mental job	24.00	28.00	1.40	25.40	4	
	Low ed.	26.00	29.00	1.45	27.33	4	Yes(0.000)
	Middle ed.	23.00	29.00	1.51	25.91	6	
	High ed.	24.00	25.00	0.50	24.36	1	
Autumn	**Urban**	20.00	27.00	1.58	23.43	7	No(0.986)
	Non-urban	20.00	27.00	2.46	23.44	7	
	Manual job	20.00	27.00	2.78	24.20	7	No(0.296)
	Mixed job	20.00	27.00	1.63	23.11	7	
	Mental job	22.00	26.00	1.53	23.83	4	
	Low ed.	23.00	27.00	1.75	22.64	4	No(0.217)
	Middle ed.	20.00	26.00	1.82	23.75	7	
	High ed.	22.00	25.00	1.42	23.56	4	
Winter	**Urban**	17.00	23.00	1.79	19.73	6	No(0.554)
	Non-urban	18.00	23.00	1.76	20.09	5	
	Manual job	17.00	22.00	1.78	19.13	5	No(0.173)
	Mixed job	17.00	23.00	1.69	19.96	6	
	Mental job	18.00	23.00	1.79	20.24	5	
	Low ed.	17.00	22.00	1.51	18.47	5	Yes(0.000)
	Middle ed.	18.00	22.00	1.45	20.03	4	
	High ed.	19.00	23.00	1.28	21.75	4	

Table 5.8 and Table 5.9 present the results of the two-tailed t-test for these three areas in each season. As a whole, only the education level classification has a significant difference between each level for the threshold limit of acceptable air temperature records in each season, with the exception of the autumn. The other two points - urban living experience and job style - do not reach the requirement limit of having a ‘significant value’ ($p<0.005$). The urban living

experience sample did not have a balanced scale of each group, in spite of the difference of air temperature but the Sig. value is not significant. For the job style classification there is no big difference in any group. The one-way ANOVA t-test method is used for testing if there is a difference between various groups for the independent variable of threshold limit records.

Table 5.9 Two-tailed t-test and one-way ANOVA t-test results of socio-cultural background in bedroom space

Bedroom		**Min.**	**Max.**	**Std. Devi.**	**Mean**	**Range**	**Sig.**
Spring	**Urban**	18.00	25.00	2.03	22.31	7	No(0.165)
	Non-urban	23	26	1.73	24.00	3	
	Manual job	20.00	25.00	1.95	22.27	5	No(0.882)
	Mixed job	18.00	26.00	2.16	22.53	8	
	Mental job	18.00	25.00	1.95	22.25	7	
	Low ed.	18.00	23.00	1.56	20.62	5	Yes(0.004)
	Middle ed.	18.00	25.00	1.85	22.65	7	
	High ed.	20.00	26.00	1.76	23.62	6	
Summer	**Urban**	23.00	29.00	1.70	25.81	6	No(0.436)
	Non-urban	24.00	28.00	1.92	26.50	4	
	Manual job	24.00	29.00	1.40	26.82	5	No(0.066)
	Mixed job	23.00	29.00	1.71	25.80	6	
	Mental job	23.00	29.00	1.67	25.27	6	
	Low ed.	25.00	29.00	1.34	27.27	4	Yes(0.000)
	Middle ed.	23.00	29.00	1.54	25.94	6	
	High ed.	23.00	25.00	0.54	24.14	2	
Autumn	**Urban**	20.00	27.00	1.63	23.54	7	No(0.886)
	Non-urban	20.00	27.00	2.46	23.44	7	
	Manual job	20.00	27.00	2.97	24.40	7	No(0.204)
	Mixed job	20.00	27.00	1.63	23.15	7	
	Mental job	22.00	26.00	1.48	24.00	4	
	Low ed.	23.00	27.00	1.75	22.64	4	No(0.169)
	Middle ed.	20.00	26.00	1.88	23.83	7	
	High ed.	22.00	25.00	1.39	23.78	4	
Winter	**Urban**	17.00	23.00	1.90	19.89	6	No(0.861)
	Non-urban	18.00	23.00	1.79	20.00	5	
	Manual job	17.00	23.00	2.05	19.25	6	No(0.233)
	Mixed job	17.00	23.00	1.73	20.09	6	
	Mental job	18.00	23.00	1.80	20.29	5	
	Low ed.	17.00	23.00	1.87	18.59	6	Yes(0.000)
	Middle ed.	18.00	22.00	1.46	20.16	4	
	High ed.	19.00	23.00	1.28	21.75	4	

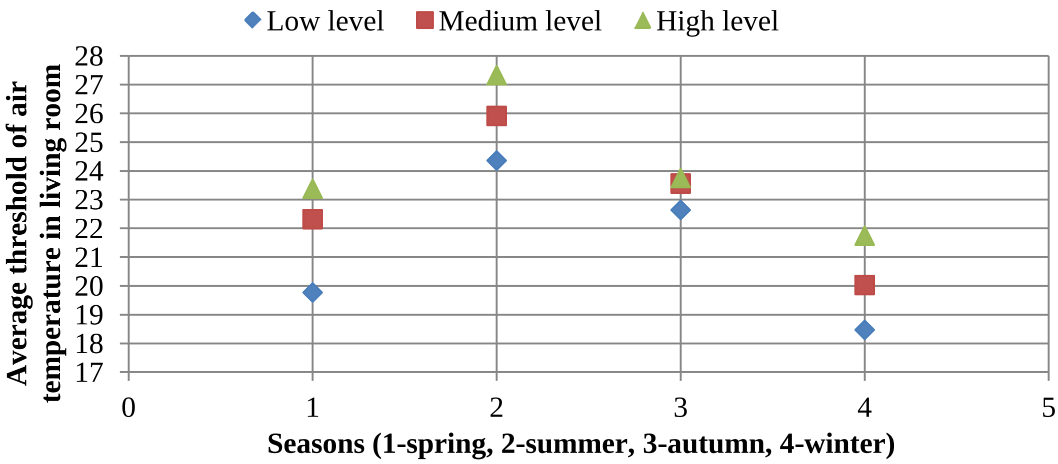


Figure 5.3 Threshold limit of indoor air temperature with education level in living room space

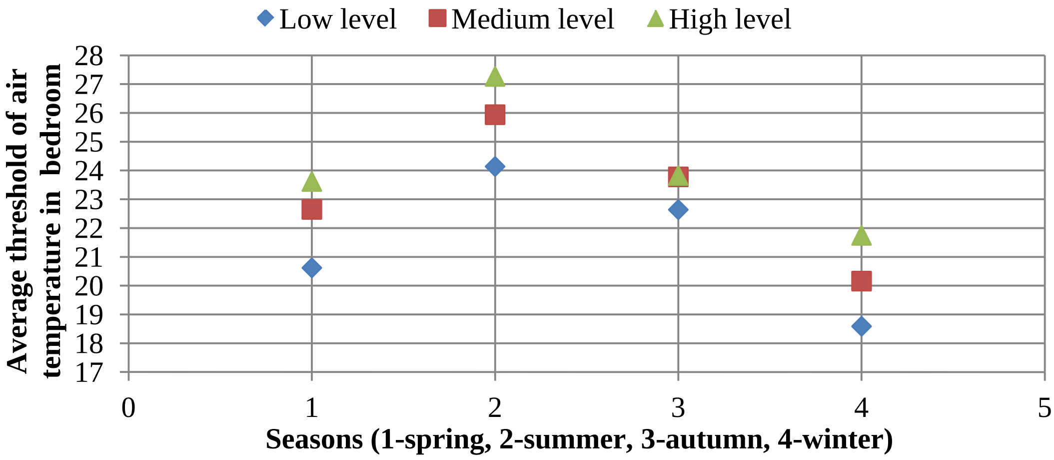


Figure 5.4 Threshold limit of indoor air temperature with education levels in bedroom space

Focusing on the education level grouping, we can find that there is a significant difference between each level in all seasons except autumn (3 refers to autumn). In spring (1 refers to spring), the data set demonstrates that the low level of education has a significant difference compared to those with a medium or high level of education, however the middle group do not reach the significant value limit ($p<0.005$) with the high-level group. In summer (2 refers to summer), these three levels have significant differences with one another. In autumn there is no significant difference between the three levels. In winter (4 refers to winter), the grouping difference returns to a high level. Therefore, various education-levels have significant differences to other groups during the extreme seasonal climates. Figure 5.3 and Figure 5.4 present the seasonal changing tendency of the average air temperature threshold for each education-level group.

For each education level, the individual deviation is different in each season surveyed. As the results of the living room space demonstrate in Table 5.8, the results of standard deviation for each education level during the spring season are nearly the same. In summer, the middle-education level group has a standard deviation result that is similar to that of the low-education level group, and it is much higher than the lowest value of the high level group During winter the low level group has a similar result to the middle level group, which are all higher values than that of the high-level group. As the results of the bedroom space demonstrate inTable 5.9, the sample deviation results during spring are also close to each other. The high level and middle level groups have relative higher values than that of the low-level group. During summer, the results for living room space are similar to those mentioned above. Regarding temperature preference in the bedroom space during winter, the standard deviation of each level group has a clear difference; the low-level group has the highest value and the high-level group has the lowest value. For the extreme season time, and even during autumn, the higher education level group has lower individual deviation values. However, this phenomenon is not obviously present during spring.

5.7.3 BUILDING LAYOUT OF THERMAL SENSATION SURVEY

Two different prototypes of Chinese residential apartment are defined as cases A and B. Case A is a kind of Y-axis apartment layout (or similar), which has a narrow front facade and rooms which h are combined as the depth direction of a Y-axis. Case B apartments have a type of X-axis layout (or similar), which has a square layout with a short depth and rooms are combined as the width direction of an X-axis. The apartment layout design is usually defined as a passive way for dealing with indoor thermal comfort problems and energy saving issues. The different apartment layouts are supposed to have some psychological effect for indoor thermal experience under variant seasonal climates. There are about 50-60 independent valid samples in each season, gathered from the questionnaire. For both cases A and B there are 40-60 participants. The summaries of participants' apartment layout surveys are listed in Table 5.10, below.

Table 5.10 Participants percentage of layout classification

Seasons		**Spring**	**Summer**	**Autumn**	**Winter**
Case	**A**	22	27	22	26
	Percentage	38.60%	44.26%	50.00%	46.43%
	B	35	34	22	30
	Percentage	61.40%	55.74%	50.00%	53.57%
Total		57	61	44	56
Percentage		100%	100%	100%	100%

Table 5.11 and Table 5.12 show the results of the two-tailed t-test in the two different building layout designs during four different seasons. The significant difference exists in hot summer or cold winter, and non-significant values are indicated during the transitional seasons (spring and autumn). The standard deviation presents a high fluctuation in transition seasons and a lower value in typical extreme seasons. This means the threshold limit values of the acceptable indoor air temperatures in extreme seasons could have higher individual deviation for the samples than that of the transition seasons. Case A has a higher standard deviation value than that of case B during spring and autumn. However, case B has a slightly higher standard deviation value than that of case A during summer and winter. The highest standard deviation values present more individual differences for the seasonal samples. The living room and bedroom space results both have a similar seasonal tendency.

Table 5.11 Summary of seasonal threshold limit of indoor air temperature in the living room spaces of two prototypes

Living room		Min.	Max.	Std.D	Mean	Range	Sig.(Case A-Case B)
Spring	**Case A**	16	25	2.65	21.55	9	No (0.265)
	Case B	18	25	2.09	22.26	7	
Sumer	**Case A**	23	28	1.12	24.78	5	Yes(0.000)
	Case B	24	29	1.49	26.79	5	
Autumn	**Case A**	20	26	1.77	23.09	6	No(0.202)
	Case B	21	27	1.72	23.77	6	
Winter	**Case A**	17	22	1.3	18.54	5	Yes(0.000)
	Case B	18	23	1.34	20.9	5	

Table 5.12 Summary of seasonal threshold limit of indoor air temperature in the bedroom spaces of two prototypes

Bedroom		Min.	Max.	Std.D	Mean	Range	Sig. (Case A-Case B)
Spring	**Case A**	18	25	2.28	22.18	7	No(0.519)
	Case B	18	26	1.88	22.54	8	
Sumer	**Case A**	23	28	1.09	24.56	5	Yes(0.000)
	Case B	24	29	1.37	26.88	5	
Autumn	**Case A**	20	26	1.78	23.14	6	No(0.156)
	Case B	21	27	1.77	23.91	6	
Winter	**Case A**	17	22	1.42	18.62	5	Yes(0.000)
	Case B	18	23	1.43	21.03	5	

5.7.4 MULTIPLE REGRESSION ANALYSIS FOR SEASONAL EFFECT

According to the statistical analysis of the respondents' subjective background data, we can find that the acceptable thermal comfort limitation is not described by a single variable and that multiple factors have a seasonal relationship with the threshold limit of indoor air temperature for acceptable thermal comfort. The method of line regression provides an approach to test each variable with the step-wise method for the line regression equation during each season. For the seasonal equation of line regression, only 'unique' variables that have high correlation coefficients of significance could be included in the final regression equation. According to the analysis results there are four variables (age group, gender, education level and case layout) which are partly included in the seasonal equation. Let,

X_1 - Age group (below 40=1, over and equal 40=2);

X_2 - Gender (male=1, female=2);

X_3 - Education level (low level=1, medium level=2, high level=3);

X_4 - Case layout (Case A=1, Case B=2);

During spring there are three variables which have strong correlation with the threshold limit of indoor air temperature for thermal comfort. They indicate that there is a thermal difference in spring caused by age, gender and education level both in living room or bedroom spaces. Their significance values are all lower than 0.05. The final regression equation has an important value which is R square value. It presents how much of the dependent variable (set-point air temperature) could be explained by these particular independent points (age, gender and education level). These two equations regarding living room and bedroom space, respectively, have 0.611(61.1%) and 0.627 (62.7%) coefficients of determination.

Table 5.13 Correlation analysis summaries between impact points and indoor air temperature during spring

Spring	Living room	T_1	Bedroom	T_2
Pearson Correlation	T_1	1.000	T_2	1.000
	Age group	.677	Age group	.684
	Gender	.518	Gender	.558
	Urban	-.172	Urban	-.187
	Job style	-.055	Job style	-.013
	Education level	.530	Education level	.502
	Case prototype	.150	Case prototype	.087
Sig. (1-tailed)	T_1	-	T_2	-
	Age group	.000	Age group	.000
	Gender	.000	Gender	.000
	Urban	.100	Urban	.082
	Job style	.343	Job style	.462
	Education level	.000	Education level	.000
	Case prototype	.132	Case prototype	.260

Spring:

Living room: $Y = 14.758+2.188X_1 + 1.244X_2 + 0.979X_3$ ($R^2=0.611$) --- (Equation5-1);

Bedroom: $Y = 15.989+1.925X_1 + 1.295X_2 + 0.733X_3$ ($R^2=0.627$)--- (Equation5-2);

In summer time one more variable is invited into the final regression equation than that in spring season, which is the difference of apartment layout. Four variables have significantly strong correlations with the threshold indoor air temperature of thermal comfort. The values of the coefficient of determination are all approximately 80%.

Table 5.14 Correlation analysis summaries between impact points and set-point indoor air temperature during summer

Summer	**Living room**	T_1	**Bedroom**	T_2
Pearson Correlation	T_1	1.000	T_2	1.000
	Age group	.809	**Age group**	.763
	Gender	.553	**Gender**	.533
	Urban living	-.136	**Urban living**	-.102
	Job style	-.268	**Job style**	-.290
	Education level	-.619	**Education level**	-.636
	Case prototype	.605	**Case prototype**	.685
Sig. (1-tailed)	T_1	-	T_2	-
	Age group	.000	**Age group**	.000
	Gender	.000	**Gender**	.000
	Urban living	.149	**Urban living**	.218
	Job style	.018	**Job style**	.012
	Education level	.000	**Education level**	.000
	Case prototype	.000	**Case prototype**	.000

Summer:

Living room: $Y = 22.068+1.905X_1 + 0.709X_2 -0.464X_3 + 0.589X_4$ ($R^2=0.808$)--- (Equation5-3);

Bedroom: $Y = 21.971+1.633X_1 + 0.56X_2-0.495X_3+ 1.056X_4$($R^2=0.798$)--- (Equation5-4);

In autumn, there are only two variables involved in the final regression equation, which are age and gender difference. These two variables have significantly strong correlation with the indoor air temperature limitation. The values of coefficient of determination reduce to the level of 67% which is similar with that of the spring season.

Table 5.15 Correlation analysis summaries between impact points and set-point indoor air temperature in autumn season

Summer	**Living room**	**T_1**	**Bedroom**	**T_2**
Pearson Correlation	**T_1**	1.000	**T_2**	1.000
	Age group	.788	**Age group**	.767
	Gender	.501	**Gender**	.528
	Urban living	-.004	**Urban living**	.022
	Job style	.021	**Job style**	.029
	Education level	.192	**Education level**	.229
	Case label	.196	**Case label**	.166
Sig. (1-tailed)	**T_1**	-	**T_2**	-
	Age group	.000	**Age group**	.000
	Gender	.000	**Gender**	.000
	Urban living	.491	**Urban living**	.443
	Job style	.445	**Job style**	.427
	Education level	.106	**Education level**	.067
	Case label	.101	**Case label**	.140

Autumn:

Living room: $Y = 18.705+2.722X_1 + 0.911X_2$ ($R^2=0.678$)--- (Equation5-5);

Bedroom: $Y = 18.663+2.649X_1 + 1.074X_2$ ($R^2=0.665$)--- (Equation5-6);

During winter there are four points involved in the thermal comfort evaluation, similar with summer. These four points (age, gender, education level and apartment layout) have significantly strong correlation with the set-point indoor air temperatures. The final regression equations of living room and bedroom spaces have a high coefficient of determination of R square values, which are all approximately 80%.

Table 5.16 Correlation analysis summaries between impact points and set-point indoor air temperature during winter

Summer	**Living room**	T_1	**Bedroom**	T_2
Pearson Correlation	T_1	1.000	T_2	1.000
	Age group	.673	**Age group**	.727
	Gender	.717	**Gender**	.731
	Urban living	-.081	**Urban living**	-.024
	Job style	.241	**Job style**	.216
	Education level	.599	**Education level**	.555
	Case label	.670	**Case label**	.654
Sig. (1-tailed)	T_1	-	T_2	-
	Age group	.000	**Age group**	.000
	Gender	.000	**Gender**	.000
	Urban living	.277	**Urban living**	.431
	Job style	.037	**Job style**	.055
	Education level	.000	**Education level**	.000
	Case label	.000	**Case label**	.000

Winter:

Living room: $Y = 13.786+1.208X_1 + 1.470X_2 + 0.552X_3 + 0.663X_4$ (R^2=0.823)- (Equation5-7);

Bedroom: $Y = 13.751+1.654X_1 + 0.949X_2+ 0.509X_3 + 0.913X_4$ (R^2=0.771)--- (Equation5-8);

The empirical formulas present the relationship between respondents' subjective background data and their threshold limitation of indoor acceptable air temperature for thermal comfort preference. For the different seasonal climates, different variables are involved in these empirical equations. They express the individual's regionally-influenced psychological tolerance capacity and local climatic thermal culture. The acceptable ranges shall be summarised for the different occupants' psychological adaptation processes. According to the regression analysis mentioned above, age group, gender, education level and apartment layout are the stabilizing factors presented in the empirical formulas.. It aims to summarise the threshold limit of indoor acceptable thermal comfort in a HSCW based on variant subjective variables of psychological impact under different seasonal climates. Moreover, there is no significant difference between living room and bedroom space. The determinate coefficient R square values are all above 0.6 which means that over 60% of the variables of psychological preference temperature could be explained by this regression equation. The extreme seasons of summer and winter have higher R square values than the transitional seasons of spring and autumn. These explanation coefficients indicate that during particularly intense climatic situations psychological impact could be more significant, especially during a hot summer.

The diversified permutations diverse range of these involved factors present various thermal comfort expectations and as a result it is difficult to define occupants' indoor thermal environment demands. Consequently, it is preferable to find a common and simple variable to replace the complex subjective background variables. The empirical equations stand for the four seasonal thermal sensation fluctuations and the seasonal climate is an effective variable for respondents' psychological thermal expectation. The regional thermal culture is based on these subjective background data collections and analysis. Therefore, a series of permutations and various combinations of data present the limit of acceptable range for each season. Comparing these findings with the typical climatic data could help obtain a simple regional empirical equation to predict psychological expectation and preference.

Table 5.17presents the summary of variables for psychological expectation during transitional seasons. During spring, there are three variables involved to determine the indoor thermal comfort expectation (age, gender and education level), thus a series of permutations are listed in the table. For example 'A1G1E1' refers to a sample occupant belonging to the younger group (below 40 years old), who is male, and is in the low education level group. The results of the analysis show the lowest minimum value is 19.17 ℃ (A1G1E1) and the highest maximum value is 24.56 ℃ (A2G2E3). The average temperature range is from 20.08 – 23.65℃ and the mean value of the spring season is about 22 ℃ (21.86℃). The t-test results express that there is a significant difference between the younger and older group, but no significant differences for gender and education level groups. During autumn, there are two variables involved for the seasonal regression equation (age and gender). The lowest minimum value is 22.34℃ (A1G1) and the highest maximum value is 25.97℃ (A2G2). Because the group classification is only composed of two modular ways, the research into significant differences within age groups and gender are inaccurate.

Table 5.18 presents the permutations of psychological expectation in summer time (extreme season). There are four variables involved for the limit of adaptation determination: age, gender, education level and apartment layout. The lowest minimum value is 23.88℃ (A1G1E3C1) and the highest maximum value is 28.01℃ (A2G2E1C2). Only age groups have any significant difference. The total range of average values is from 24.39-27.50℃ and the total mean value is 25.94℃. This almost reaches the lower limit of indoor thermal environment control range 26-28℃ for energy efficiency during summer time in a HSCW zone. Table 5.19 presents the summary of results during winter. There are four variables involved for the limit of acceptable thermal comfort: age, gender, education level and apartment layout. The lowest minimum value is 17.68℃ (A1G1E1C1) and the highest maximum value is 22.12℃ (A2G2E3C2). The average range of indoor air temperature is from 18.23^{o}C to 21.57^{o}C and the mean value is 19.90^{o}C, which is 2-3^{o}C higher than the indoor thermal environment control range of 16-18^{o}C for energy efficiency during winter time in a HSCW zone. The t-test results reveal that age and gender have significant differences within each group during the winter season.

Table 5.17 Summary tabulation of psychological expectation permutation in transitional seasons

Spring	Age		Gender		Education level			Average
Permutations of psychological expectation	A1G1E1	A2G1E1	A1G1E1	A1G2E1	A1G1E1	A1G1E2	A1G1E3	
	A1G1E2	A2G1E2	A1G1E2	A1G2E2	A1G2E1	A1G2E2	A1G2E3	
	A1G1E3	A2G1E3	A1G1E3	A1G2E3	A2G1E1	A2G1E2	A2G1E3	
	A1G2E1	A2G2E1	A2G1E1	A2G2E1	A2G2E1	A2G2E2	A2G2E3	
	A1G2E2	A2G2E2	A2G1E2	A2G2E2				
	A1G2E3	A2G2E3	A2G1E3	A2G2E3				
Min.	19.17	21.36	19.17	20.41	19.17	20.15	21.13	20.08
Max.	22.37	24.56	23.32	24.56	22.6	23.58	24.56	23.65
Std. deviation	1.11	1.11	1.48	1.48	1.45	1.45	1.45	1.36
Mean	20.77	22.96	21.24	22.49	20.89	21.86	22.84	21.86
Rang	3.2	3.2	4.15	4.15	3.43	3.43	3.43	3.57
Sig. (within groups)	Yes (0.007)		No (0.177)		No (0.218)			

Autumn	Age		Gender		Average
Psychological impact of permutations	A1G1	A2G1	A1G1	A1G2	
	A1G2	A2G2	A2G1	A2G2	
Min.	22.34	25.06	22.34	23.25	23.25
Max.	23.25	25.97	25.06	25.97	25.06
Std. deviation	0.64	0.64	1.92	1.92	1.28
Mean	22.79	25.52	23.7	24.61	24.16
Rang	0.91	0.91	2.72	2.72	1.82
Sig. (within groups)	No (0.052)		No (0.683)		

Table 5.18 Summary tabulation of psychological expectation permutation in summer season

Summer	Age		Gender		Education level			Layout design		Average
Permutations of psychological expectation	A1G1E1C1	A2G1E1C1	A1G1E1C1	A1G2E1C1	A1G1E1C1	A1G1E2C1	A1G1E3C1	A1G1E1C1	A1G1E1C2	
	A1G1E2C1	A2G1E2C1	A1G1E2C1	A1G2E2C1	A1G2E1C1	A1G2E2C1	A1G2E3C1	A1G1E2C1	A1G1E2C2	
	A1G1E3C1	A2G1E3C1	A1G1E3C1	A1G2E3C1	A2G1E1C1	A2G1E2C1	A2G1E3C1	A1G1E3C1	A1G1E3C2	
	A1G2E1C1	A2G2E1C1	A2G1E1C1	A2G2E1C1	A2G2E1C1	A2G2E2C1	A2G2E3C1	A2G1E1C1	A2G1E1C2	
	A1G2E2C1	A2G2E2C1	A2G1E2C1	A2G2E2C1	A1G1E1C2	A1G1E2C2	A1G1E3C2	A2G1E2C1	A2G1E2C2	
	A1G2E3C1	A2G2E3C1	A2G1E3C1	A2G2E3C1	A1G2E1C2	A1G2E2C2	A1G2E3C2	A2G1E3C1	A2G1E3C2	
	A1G1E1C2	A2G1E1C2	A1G1E1C2	A1G2E1C2	A2G1E1C2	A2G1E2C2	A2G1E3C2	A1G2E1C1	A1G2E1C2	
	A1G1E2C2	A2G1E2C2	A1G1E2C2	A1G2E2C2	A2G2E1C2	A2G2E2C2	A2G2E3C2	A1G2E2C1	A1G2E2C2	
	A1G1E3C2	A2G1E3C2	A1G1E3C2	A1G2E3C2				A1G2E3C1	A1G2E3C2	
	A1G2E1C2	A2G2E1C2	A2G1E1C2	A2G2E1C2				A2G2E1C1	A2G2E1C2	
	A1G2E2C2	A2G2E2C2	A2G1E2C2	A2G2E2C2				A2G2E2C1	A2G2E2C2	
	A1G2E3C2	A2G2E3C2	A2G1E3C2	A2G2E3C2				A2G2E3C1	A2G2E3C2	
Min.	23.88	25.78	23.88	24.59	24.81	24.34	23.88	23.88	24.47	24.39
Max.	26.11	28.01	27.3	28.01	28.01	27.55	27.08	27.42	28.01	27.50
Std. deviation	0.62	0.62	1.11	1.11	1.13	1.13	1.13	1.13	1.13	1.13
Mean	24.99	26.9	25.59	26.3	26.41	25.94	25.48	25.65	26.24	25.94
Rang	2.23	2.23	3.42	3.42	3.2	3.2	3.2	3.54	3.54	3.20
Sig. (within groups)	Yes (0.000)		No (0.133)		No (0.282)			No (0.216)		

Table 5.19 Summary tabulation of psychological impact permutation in winter season

Winter	**Age**		**Gender**		**Education level**			**Layout design**		**Average**
Psychological impact of permutations	A1G1E1C1	A2G1E1C1	A1G1E1C1	A1G2E1C1	A1G1E1C1	A1G1E2C1	A1G1E3C1	A1G1E1C1	A1G1E1C2	
	A1G1E2C1	A2G1E2C1	A1G1E2C1	A1G2E2C1	A1G2E1C1	A1G2E2C1	A1G2E3C1	A1G1E2C1	A1G1E2C2	
	A1G1E3C1	A2G1E3C1	A1G1E3C1	A1G2E3C1	A2G1E1C1	A2G1E2C1	A2G1E3C1	A1G1E3C1	A1G1E3C2	
	A1G2E1C1	A2G2E1C1	A2G1E1C1	A2G2E1C1	A2G2E1C1	A2G2E2C1	A2G2E3C1	A2G1E1C1	A2G1E1C2	
	A1G2E2C1	A2G2E2C1	A2G1E2C1	A2G2E2C1	A1G1E1C2	A1G1E2C2	A1G1E3C2	A2G1E2C1	A2G1E2C2	
	A1G2E3C1	A2G2E3C1	A2G1E3C1	A2G2E3C1	A1G2E1C2	A1G2E2C2	A1G2E3C2	A2G1E3C1	A2G1E3C2	
	A1G1E1C2	A2G1E1C2	A1G1E1C2	A1G2E1C2	A2G1E1C2	A2G1E2C2	A2G1E3C2	A1G2E1C1	A1G2E1C2	
	A1G1E2C2	A2G1E2C2	A1G1E2C2	A1G2E2C2	A2G2E1C2	A2G2E2C2	A2G2E3C2	A1G2E2C1	A1G2E2C2	
	A1G1E3C2	A2G1E3C2	A1G1E3C2	A1G2E3C2				A1G2E3C1	A1G2E3C2	
	A1G2E1C2	A2G2E1C2	A2G1E1C2	A2G2E1C2				A2G2E1C1	A2G2E1C2	
	A1G2E2C2	A2G2E2C2	A2G1E2C2	A2G2E2C2				A2G2E2C1	A2G2E2C2	
	A1G2E3C2	A2G2E3C2	A2G1E3C2	A2G2E3C2				A2G2E3C1	A2G2E3C2	
Min.	17.68	18.89	17.68	19.15	17.68	18.23	18.78	17.68	18.34	18.23
Max.	20.92	22.12	20.65	22.12	21.02	21.57	22.12	21.46	22.12	21.57
Std. deviation	0.96	0.96	0.86	0.86	1.08	1.08	1.08	1.1	1.1	1.13
Mean	19.3	20.51	19.17	20.64	19.35	19.9	20.45	19.57	20.23	19.90
Rang	3.24	3.24	2.98	2.98	3.34	3.34	3.34	3.78	3.78	3.20
Sig. (within groups)	Yes (0.006)		Yes (0.000)		No (0.147)			No (0.154)		

According to the literature review of the HSCW zone's climatic situation in the Chapter 2, the middle month of each season is respectively April for spring, July for summer time, October for autumn and January for winter. The historical data set provides the minimum and maximum average values of the outdoor monthly air temperature, and matching the minimum and maximum value of climatic figures with the lower and upper average limit of psychological expectation for each season reveals that there are two linear equations which could be used to summarise the upper and lower margins of the relationship between occupants' psychological expectation for indoor thermal comfort and the outdoor mean monthly temperature. Two equations are listed below and high level determining coefficients of R square values means these two equations have good credibility.

For a mixed mode residential apartment:

Lower margin: $T_{comf} = 0.286T_{o.av} + 17.61$ ($R^2 = 0.836$)--- (Equation5-9);

Upper margin: $T_{comf} = 0.247T_{o.av} + 19.15$ ($R^2 = 0.935$)--- (Equation5-10);

5.8 THE COGNITION OF THERMAL COMFORT AND ENERGY EFFICIENCY IN A HSCW ZONE

In this section the questionnaire study is going to investigate the regional specifics of thermal comfort expectation and personal preference of energy efficiency. This is important for understanding the local thermal culture and subjective psychological thermal expectation. For example, if the occupants have high energy saving cognition they would set relatively low indoor air temperatures to satisfy their person thermal comfort. There are three sub-points in this part of the questionnaire survey. The first point concerns the personal preference of conscious temperature, from absolute thermal comfort against absolute energy saving. The second sub-point concerns the factor of energy use. There are four factors of which two are subjective and two are objective, and which include occupant's living habit, social status of income, building environment control of energy efficiency implementation and regional climate. The third sub-point concerns the factor of thermal comfort, and there are three conventional impact factors of physiology, psychology and behaviour.

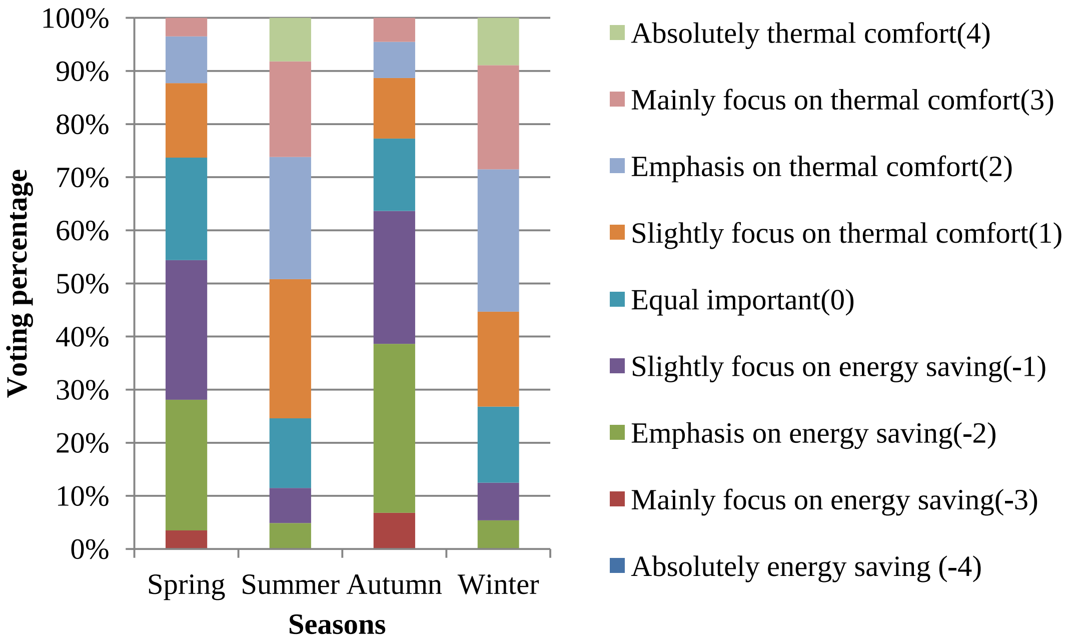


Figure 5.5 Attitude percentage of energy saving and thermal comfort in four seasons

Table 5.20 Summaries of the percentage of human attitude to energy saving and thermal comfort in four seasons

	Attitude of energy saving and thermal comfort									
	-4	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**Total**
Spring	0	2	14	15	11	8	5	2	0	57
Percentage	0	3.5%	24.6%	26.3%	19.3%	14.0%	8.8%	3.5%	0	100%
Summer	0	0	3	4	8	16	14	11	5	61
Percentage	0	0	4.9%	6.6%	13.1%	26.2%	23.0%	18.0%	8.2%	100%
Autumn	0	3	14	11	6	5	3	2	0	44
Percentage	0	6.8%	31.8%	25.0%	13.6%	11.5%	6.8%	4.5%	0	100%
Winter	0	0	3	4	8	10	15	11	5	56
Percentage	0	0	5.4%	7.1%	14.3%	17.9%	26.7%	19.6%	8.9%	100%

According to the results collected above, the attitude of interviewees toward the choice of energy saving or thermal comfort fluctuates. In the transitional seasons, there is more attention towards energy saving than thermal comfort if there is a relatively moderate climate. In contrast, more attention is focused on thermal comfort during extreme seasons of hot summer and cold winter. Concerning the differences between spring and autumn, the percentage of energy saving supporters increases during autumn, and with shifting sights to the extreme season of winter, there is an increase in the amount of supporters of thermal comfort. According to the interview communication, participants use more adaptive responses to cooling down an overheated environment by opening windows for natural ventilation, shading the room by drawing curtains and or using a sun visor, wearing less or thinner clothing, drinking cooling water and keeping low levels of indoor activity, and if necessary, gradually using cooling facilities. Even if using electrical equipment, there are still several choices for energy saving, for example one may try using a paper fan, and then using a low-power fan or cooling fan, then last by using air-conditioner with high levels of COP or EER values. However, in cold situations fewer implements are utilised in a passive way for heating up a cold environment because there is no central heating system and the main implements are electrical heaters and air-conditioning.

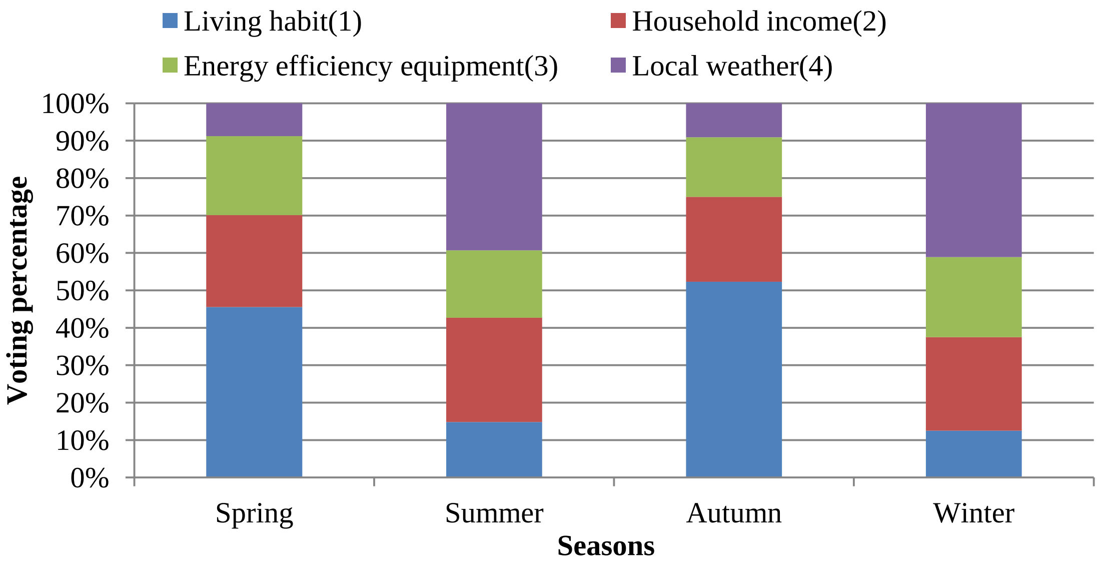


Figure 5.6 Voting results of main factors in energy consumption

Table 5.21 Summary of the percentage of factors impacting on voting for energy consumption in four seasons

	Energy consumption factor				
	1	**2**	**3**	**4**	**Total**
Spring	26	14	12	5	57
Percentage	45.6%	24.6%	21.1%	8.8%	100%
Summer	9	17	11	24	61
Percentage	14.8%	27.9%	18.0%	39.3%	100%
Autumn	23	10	7	4	44
Percentage	52.3%	22.7%	15.9%	9.1%	100%
Winter	7	14	12	23	56
Percentage	12.5%	25.0%	21.4%	41.1%	100%

For the energy consumption in residential building, there are four significant points: personal characteristics of energy use (living habit), social integrative status of economic affordability (household income), energy efficiency capacity of the indoor facilities (efficiency equipment) and regional climatic situation (local weather). All interviewees presented their personal understanding of thermal comfort and their attitude towards energy saving on the basis of their individual seasonal psychological ideas about thermal sensation. Figure 5.6 and Table 5.21present the main factors which impacted on voting and the percentage of each factor during different seasons. They express that occupants' living habits dominate in the transitional seasons of spring (approximately 45%) and autumn (over 50%). The weather situation determines the energy use during extreme seasons of summer and winter, which are all at roughly 40%. Living habits and weather situations are two dominating factors affecting energy consumption, and they are more significant in determining occupants' psychological thermal preference than the other two factors of household income and energy efficiency.. The main reason is that the indoor thermal environment is controlled by mixed modes without the aids of central heating and or a main cooling system, therefore the determination coefficient is flexible for energy use and there are multiple cheap and passive ways to restore indoor thermal comfort. Moreover there is a sceptical attitude towards balancing the high investment that must go into energy efficiency facilities during the initial stage and getting rewarded financially later on. This is the reason that the percentage of household income voting is even a little bit higher than the equipment option.

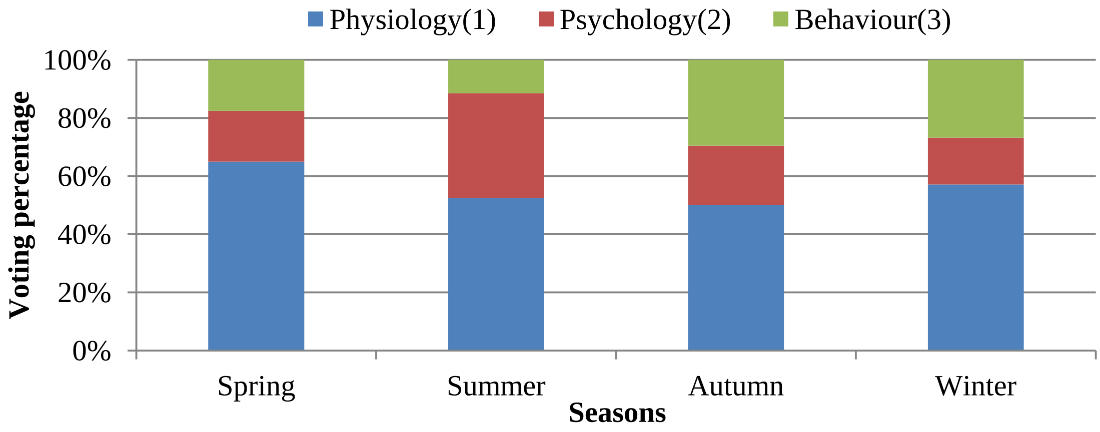


Figure 5.7 Voting results of main factor in adaptive thermal comfort

Table 5.22 Summary of the percentage of factors impacting voting for adaptive thermal comfort in four seasons

	Thermal comfort factor			
	Physiology	**Psychology**	**Behaviour**	**Total**
Spring	37	10	10	57
Percentage	64.9%	17.5%	17.5%	100%
Summer	32	22	7	61
Percentage	52.5%	36.1%	11.5%	100%
Autumn	22	9	13	44
Percentage	50.0%	20.5%	29.5%	100%
Winter	32	9	15	56
Percentage	57.1%	16.1%	26.8%	100%

Thermal comfort is a comprehensive definition of feeling without any overheating and overcooling. It is not a single value of unique parameters and it is a flexible band within a person’s satisfaction and tolerance range. Based on the adaptive thermal comfort theory this band is limited or adjusted by three factors: physiological, psychological and behavioural factors. Figure 5.7 draws the percentage accumulation histogram of preference results for determining thermal comfort. Table 5.22shows the summary of changing ratios within different seasons. The physiological factor is the most important factor, with all four seasonal physiological impact votes reaching between 50-65%. The seasonal difference between psychological factors and behavioural factors exists in hot summer; psychological factors are realised as having a more significant determining role than behavioural factors.. In wintertime more people think the behavioural factor has greater determination than the psychological factor. This is also the case for autumn. In springtime the psychological factor is of equal importance to behavioural factors.

5.9 CONCLUSIONS

The field study of subjective thermal perception for indoor thermal comfort took place in two typical prototypes of Chinese residential apartment located in a HSCW zone. It is revealed that the occupant’s thermal perception with psychological expectation and adaptation in residential buildings are various and strongly correlated with subjective background. Moreover, the personal thermal preference has its own fluctuation following the seasonal climate changes. This chapter’s content is based on the field study data set collected from a questionnaire survey and a few days of recording thermal experience regarding the personal acceptable thermal comfort limit. Statistical analysis is used with SPSS software. The detailed findings from this method have been summarised as follows:

- First of all, according to the field study of indoor thermal environment, the regional residential apartments’ thermal environment is controlled using mixed modes without any central heating or cooling systems. Air-conditioning (AC) is the most popular facility for indoor heating and cooling. Over 90% of interviewees’ apartments are equipped with AC. However the AC device is not always the first choice of indoor mechanism adjustment, especially in the living room space where a small low-powered device is usually the first choice for heating and cooling. In the bedroom space respondents usually choose AC as the first choice for heating but not for cooling.
- Secondly, as statistical analysis in this chapter study shows, we found these subjective factors of psychological preference for indoor acceptable thermal comfort have seasonal differences. The anthropological factors of age and gender always have significant differences in all seasons. For socio-cultural background factors, only the education level of respondents has significant differences during spring, summer and winter, but not autumn. The different building layouts cause the threshold limits of indoor acceptable thermal comfort to have significant differences in extreme seasons (summer and winter) only.

- Thirdly, the age group analysis indicate that in the transitional seasons of spring and autumn younger respondents have more individual differences and older respondents have higher preference for warmer situations. In the extreme seasons of summer and winter, although the older respondents still like a warmer situation, the individual differences of the two groups are equal.
- Fourthly, the gender difference indicates that females like a warmer situation with a higher threshold limit of acceptable thermal comfort than the male group. The female group has a wider temperature range than the male group during spring, but a smaller range during autumn. Both groups have the same temperature range in extreme seasons. However there is a seasonal difference for inter-group individual differences. Female standard deviation is higher than the male group during spring, summer and winter, but not during autumn.
- Fifthly, the education level variables have no significant difference in autumn time and the other three seasons have very significant diversity in this city of China's HSCW zone. We can find that respondents with higher education levels recorded warmer temperatures in cold situations and cooler temperature limits in hot situations. This means that typically more energy would be used by this high education level group for restoring thermal comfort and the thermal comfort preference threshold limit is even further away from the benchmark of a HSCW zone's design code for low-energy residential buildings (16-18^{o}C in winter and 26-28^{o}C in summer).
- Sixthly, the building layout differences make the thermal perception different from the limit of acceptable thermal comfort. Different prototypes result in a different psychological preference. The threshold limits of air temperature in case B are all higher than that of case A in all four seasons. There is more potential of energy used to heat during cold winter in case B and more potential of energy used for cooling during hot summer in case A.
- Seventhly, the research in this chapter presented a series of seasonal linear regression equations using mathematic analysis, and each equation indicates the seasonal psychological preference limit of indoor thermal comfort in the HSCW zone. We can find that extreme seasons' empirical equations have higher determining coefficients of 'R' square values than that of transitional seasons. According to the multiple variables in the seasonal equations, it is thought too complicated to be applied to local psychological thermal preference research. The climatic data input could simplify the seasonal empirical equations to equations which show the upper and lower acceptable thermal comfort limit margins within different outdoor monthly air temperatures. There is the thermal comfort band with regional psychological preference (adjustment) and two equations (5-9) and (5-10) have high levels of R square value (R^2 = 0.8-0.9).

- Eighthly, personal attitudes of energy saving and thermal comfort have seasonal differences which are presented in this chapter. More preference for energy saving happened in the transitional seasons of spring and autumn. However a higher percentage of support for thermal comfort occurred in the extreme seasons of hot summer and cold winter. Participants thought that there are more adaptive responses during transitional seasons because there are few potential indoor overheating or overcooling problems. They usually restore the indoor thermal comfort first by opening windows with cross natural ventilation, shading with drawing interior curtains and outside additional sun visors, wearing less clothing, drinking cool water and keeping a low level of indoor activity, and if necessary, gradually using small power facilities before using high levels of COP or EER air-conditioning. For the detailed study of energy consumption and local thermal comfort attitudes, nearly 50% of participants thought the level of energy used was based on living habits through the transitional seasons, with more people preferring to concern themselves with energy saving in these seasons. However, in extreme seasons the dominant percentage of energy use is dependent upon the local weather situation, and this explains the justification of the higher determining coefficient of the seasonal linear regression equations obtained during extreme seasons. The physiological impact is relevant for determining thermal comfort through all seasons. Psychological impact is found to be more important than the behavioural impact during hot summer time and the opposite result is found during a cold winter.
- Psychological impact and preference is a dynamic empirical research with variant participants’ background and consciousness of thermal experience being taken into consideration. It is a fluctuating process with significant seasonal differences according to weather situations. The further challenge is how to undertake more comprehensive surveys to collect regional data within more respondents’ differing classifications. The difficulty is due to the complex variables of psychological thermal preference and the sensitivity of occupants’ actual needs for adaptive thermal comfort demand. Subjective background information is very important in the study of the psychological preference of acceptable thermal comfort, and it would affect the buildings’ performance of thermal comfort and energy consumption. Therefore, this research could be involved in the design process of building work and in supporting more necessary links with governance mechanisms of information feedback and energy strategies. It is more useful to dynamically control the indoor thermal environment and is a good starting point for intelligent residential buildings of the future.

CHAPTER 6 PARAMETRIC STUDY OF SIMULATION WORK FOR RESIDENTIAL BUILDING PERFORMANCE

6

6.1 INTRODUCTION

As the quantity and quality researches of field study for these two selected cases in the early chapters, a series of scheduled people participation data and thermal environment control research are used for simulation work input in this chapter. More detailed research and parametric study on the residential building environments are required for the further studies of regional sustainable designs in the China HSCW zone. It is found that, in both cases, use of adaptive thermal comfort mechanisms result in higher energy use than that based on energy efficiency design standards, but that they use less energy than the environmental design which is controlled by the current healthy housing technical recommendations in China. For the different prototypes the effects of adaptive thermal comfort scenarios are various in terms of energy use when heating or cooling. The adaptive thermal comfort theory provides a better explanation of the subjective occupants' participation in their assessment of the indoor environment sensation and can even determine the energy use for thermal adjustment. Consequently, the technique of during a parametric analysis present the effects of occupancy density and the subjective set-point air temperature control. In this paper, the simulations raise questions about the relationship between a building's shape and levels of energy conservation. It is found that the building shape coefficient is not the dominating parameter for energy saving. In fact, the energy use per unit of indoor floor area has a more significant role in the efficiency of a building's thermal performance. Section 6.2 gives a detailed literature review of parametric design for building environment research. Section 6.3 presents the research methods with six points of case study, simulation scenarios introduction, occupancy schedule, lighting schedule, HVAC schedule and simulation tool description. Section 6.4 presents the simulation work for indoor thermal comfort perception. Section 6.5 presents energy consumption performance within three different thermal scenarios context. Section 6.6 gives a study of subjective participation for building performance. The section 6.7 presents a query of building shape coefficient for a determination of building energy efficiency.

6.2 PARAMETRIC DESIGN

An increasing urban population and the China new residential building construction make the China's national development strategy turn to 'green building' technology, and it has been announced in the special planning outline of China's 12th 'Five-Year Plan' (Wu and Xu 2013; Ye et al. 2013). The green building strategy has two main development targets in the construction of new buildings: to produce a comfortable building environment and to encourage energy-efficiency through energy conservation techniques. However, studies examining the relationship between buildings and their occupants were not undertaken until the large-scale occupant survey during the first generation of green buildings in China, developed by Gou et al (Gou et al. 2013). The green building definition states that in the life-cycle of building operations, buildings should be energy- and resource-efficient as far as possible, whilst the building environment should be healthy and comfortable. The green building revolution has proved to be a significant and irreversible event in the building sector for the improvement of building environments in urban areas and global environments (USEPA 2009; USGBC 2009). According to the intense research of forty green projects and hundreds of existing studies' reviews developed by Lawrence Berkeley Laboratory and Capital E Group (Kats et al. 2003), the cost of occupants' comfort, productivity and health were larger than the costs spent on construction and operation. The U.S. Green Building Council launched a survey to present the sustainable building design and identify how it could impact human living positively. This would become a significant study of green building research (Heerwagen 2000; Reeder 2010; Sighn et al. 2010). Two large-scale studies were launched by the Center for Built Environment (CBE) at the University of California Berkeley in North America (Abbazadeh et al. 2006; G. S. Brager and Baker 2008; Leaman and Bordass 2007) and Building Uses Studies Ltd. (BUS) in the U.K (Leaman and Bordass 2007). These two studies highlighted the limitations of green building performance and occupant comfort and satisfaction. (Xiuzhang Fu 2002b)

This parametric study aims to compare two different selected cases in terms of the diversity of the building's thermal performance. Field studies into adaptive thermal comfort provide a novel point of the simulation scenario. The first research question uses current thermal environment design strategies to look at how to challenge the demand for thermal comfort whilst still encouraging energy conservation in Chinese residential buildings in a HSCW zone. The second research question examines the differences of applying the adaptive thermal comfort strategy in these two selected cases. The third research question aims to question the significance of building shape in energy use in current Chinese building-design standards. Building shape is viewed as a conclusive indicator of a building's energy efficiency and is a mandatory consideration whichh is met with approval in design documents. The fourth research question will discuss the effect of subjective participation.

6.3 RESEARCH METHOD

A building’s successful thermal performance is complex and based on a comprehensive index. Related studies only focus on one point of building design, construction, management or otherwise. In the first part of this parametric study, the modelling methods of two selected cases are used to investigate the buildings’ performance when different controlled environment scenarios are introduced. In the second part of this research, the computer modelling method is used to simulate a square building, and a parametric analysis is applied for adding the secondary variable of subjective participation to demonstrate the changing of a building’s performance caused by the first variable of objective building design (external windows area and infiltration design). For the third part of this parametric study, the building shape coefficient effect is discussed with the aid of the simulation of building shapes, height and internal floor designs. Therefore in the methods section there are three subfields: case study, simulation scenarios and simulation tool introduction.

6.3.1 TWO PROTOTYPES OF CASE STUDY

The two selected cases have different building layouts with different room combinations, presented in CHAPTER 3. The majority of external windows face a north-south orientation. They both have four bedrooms and one living room, and only the bedrooms and living room are controlled by HVAC installations (involved with thermal calculation). One is case A which has a longer unit depth, with a Y-axis room combination. The other one is case B which has a square unit-layout with an X-axis room combination. The materials used in the buildings’ construction are the same for both models. Table 6.1 and Table 6.2 show the models’ construction material of simulation for both cases. The U-value is an important factor for thermal environment simulation, especially for any external wall insulation, and external windows. The external wall has a common external insulation layer and, when designing this, the U-value should not be over 1.0 W/m^2-K (it is good level in China). The value of an external window is designed below 2.0 W/m^2-K.

Table 6.1 The building construction design and U-value

Components	Material layer	Thickness (m)	U-value (W/m^2-K)
External wall	Cement/plaster/mortar-cement plaster (Outer)	0.015	0.946
	EPS Expanded Polystyrene (Lightweight)	0.02	
	Hollow clay brick	0.20	
	Cement/plaster/mortar-cement plaster (Inner)	0.015	
Internal wall:	Plaster (Dense)	0.02	2.061
	Brick-burned	0.20	
	Plaster (Dense)	0.02	
Floor:	Cast Concrete	0.20	2.237
Flat roof:	Ceramic floor tiles Dry	0.005	0.743
	Concrete, cast-lightweight	0.04	
	Glass Fiber Quilt	0.005	
	EPS Expanded Polystyrene (Lightweight)	0.030	
	Cement/plaster/mortar-cement plaster	0.020	
	Asphalt Mastic Roofing	0.005	
	Cement plaster	0.020	
	Gypsum plaster, perlite aggregate	0.005	
	Concrete, cast-dense, reinforced	0.200	
Internal door	Solid hardwood door (normally hung)	0.042	2.500
External door	Wooden flush panel hollow core door	0.042	2.557

Table 6.2 The building openings construction and U-value

Components	Material layer	Thickness (m)	U-value (W/m^2-K)
Internal window	UPVC window frame + DblClr 6mm/6mm Air	0.018	3.157
External window	UPVC window frame + DblLoE (e2=0.1) Clr 6mm/ 13mm Air	0.025	1.772
Frame construction	UPVC window frame (Polyvinlychloride)	0.02	3.467

6.3.2 SIMULATION SCENARIO DESIGN

The environmental control is composed of the indoor air temperature set-point and the value of the set-back air temperature. The set-point value defines the ideal temperature required for cooling or heating, and the set-back value is designed to consider the low level of cooling or heating required at a specific time in the occupancy schedule. This creates a real effect of thermal control within residential buildings in a HSCW zone of China. In this study there are three scenarios designed using the simulation technique. One scenario is extracted from a local residential building design’s standard of energy efficiency (16-18 in winter and 26-28 in summer). A second scenario is extracted from China’s healthy housing technical essentials (18-22 in winter and 24-28 in summer), and a third is the comfortable air temperature range used in a field study about adaptive thermal comfort.

By using the “Black Box” theory developed by Yao (R. Yao 1997; R. Yao et al. 2009; R. Yao et al. 2010), the equations of aPMV model give a very good explanation of the process of human thermal adaptation to deal with the ambient thermal discomfort stimulation. The aPMV model is based on Fanger’s steady-state heat-balance model (PMV model) and considers more adaptive approaches of psychological and behavioural adaptations from the results found by Nicol et al, (J. Fergus Nicol et al. 1999), Sharma and Ali (Sharma and Ali 1986), Busch (Busch 1992). According to Yao’s cybernetics research of “Black Box”, the logic graph and aPMV model equation derivations are listed below:

Equations (1) to (6) indicate the theoretical framework of the adaptive thermal comfort theory and the adaptive coefficient ‘λ’. The aim of this simulation study is to use the adaptive thermal comfort range based on the regional adaptive coefficient ‘λ’ as the scenario input of the indoor thermal environment control.The scenario of adaptive thermal comfort is a consequence of a field study that is based on a subjective questionnaire and objective on-site measurement. The actual mean votes (or preferences) of thermal sensation (AMV) are obtained with the questionnaire which uses a seven-point scale based on the Bedford scale or ‘comfort vote’ of the ASHREA standard (J. F. Nicol and Humphreys 2002a). The PMV model calculation factors are all obtained from field study and a large data set. The two equations listed below are the field study’s findings for the indoor thermal sensation alongside the actual indoor air temperature.

As the thermal sensation logic formulas presented indicate - equations (4-1), (4-2) and (4-3) - the least square method has been used to calculate the adaptive coefficient of the ‘λ’ value. The PMV calculation results and AMV records are defined as pairs of inputs (x, y). The (x, y) function curve is deviated by the least square method to fit each pair of data points. In each field study (summer or winter), there are 31 sets of data during summer in case A, 28 sets during summer in case B, 43 sets of data during winter in case A and 36 sets during winter in case B. By using equation (4-6), the adaptive coefficients for two prototypes of cases in summer and winter can be calculated. When they are dragged into the adaptive coefficient formula equation (4-15), (4-16), (4-17) and (4-18) are relevant, listed below:

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1+0.174\times\mathrm{PMV})}$---(Summer, case A)--- (Equation4-15);

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1+0.215\times\mathrm{PMV})}$---(Summer, case B)--- (Equation4-16);

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1-0.192\times\mathrm{PMV})}$---(Winter, case A)--- (Equation4-17);

$\mathrm{aPMV} = \frac{\mathrm{PMV}}{(1-0.072\times\mathrm{PMV})}$---(Winter, case B)--- (Equation4-18);

According to the aPMV model equations above, the PMV calculation values are corrected to those of aPMV data set. By using the linear regression analysis, the relationship between aPMV values and indoor air temperature could be summarised as two equations for two selected cases (for both warm and cold indoor situations).

$\mathrm{aPMV}_A = 0.167T_{ia} - 3.578$ ($R^2 = 0.99$) --- (Equation4-21);

$\mathrm{aPMV}_B = 0.174T_{ia} - 3.926$ ($R^2 = 0.95$) --- (Equation4-22);

Equations (4-21) and (4-22) give the acceptable range from 0 to -1 for case A as 15.4-21.4 °C in cold conditions with the range from 0 to 1 as 21.4-27.4 °C in hot conditions (21.4 °C is the neutral temperature for case A). In case B it is 16.8-22.6 °C in cold conditions and 22.6-28.3 °C in hot conditions (22.6 °C is the neutral temperature for case B). The temperature at which the air is considered as neutral is designed as the set-point, the lower limit is designed as the heating set-back point and the upper limit is designed as the cooling set-back point. Table 6.3 shows three scenarios of simulation input. The HVAC supply temperatures are defined as higher than the set-point temperature (neutral point) for heating and lower than for cooling, and consequently the heating supply or cooling supply is designed respectively with the deviation of 2°C of the set-point value.

In a HSCW zone, a residential building is usually controlled using mixed modes of HVAC air conditioning and natural ventilation. Natural ventilation provides fresh air and cools down the indoor air temperature when uncomfortably warm, but it does result in an unwanted waste of energy (J. Liu et al. 2012b; Yin et al. 2010). In this research, the natural ventilation temperature is designed as the equal value of the set-back temperature which prevents the indoor environment from any overcooling which might be caused by natural ventilation. The natural ventilation simulation is set to the ‘Scheduled’ option in the DesignBuilder software according to the minimum fresh air required per person (30 m^3/h-per person equal about 8.3 l/s-per person). The scheduled natural ventilation becomes active when the indoor air temperature is higher than the natural ventilation cooling set-point temperature, and the difference between the indoor and outdoor air temperature is less than the maximum value of the inside-outside delta temperature setting (-50 means natural ventilation is unrestricted by the inside-outside delta temperature setting).

Table 6.3 Simulation input of thermal environment control and HVAC setting up

Thermal environment control	**Scenario 1**	**Scenario 2**	**Scenario 3**
Heating set-point	18	22	21.4
Heating set-back	16	18	15.4
Cooling set-point	26	24	21.4
Cooling set-back	28	28	27.4
HVAC supply heating	20	24	23.4
HVAC supply cooling	24	22	19.4
Natural ventilation cooling	16	18	15.4
Max in-out Delta T	-50	-50	-50

6.3.3 BUILDING OPERATION OCCUPANCY SCHEDULE

The activity schedule is a description of building usage pattern linked with occupancy rate, human activity metabolic level, The requirement of domestic hot warter (DHW) and indoor environmental control (set-point temperature and heating or cooling set back, natural or mechanism ventilation requirement), and some other indoor heat gains from computers, office equipment, catering and miscellaneous. There are some assumptions about simulation input of occupant behavioural schedules (occupancy, lighting and HVAC use).

First of all in this study considering common situations of residential building in China the DHW input setting, the mechanical ventilation setting and some non-domestic equipments setting totally do not account for the indoor thermal comfort simulation and energy use calculation. These issues do not make too much different impact for the subjective assessment of China residential building thermal environment. Especially for mixed control (SAC and natural ventilation) dwelling in HSCW zone, which could effect total energy use but not for indoor thermal comfort demand.

Secondly, some parameters are fixed in the simulation work, such as the occupancy density and human indoor metabolic level (activity and clothing rate). The occupancy density is based on the difference of two cases' floor area and the people's activity schedules are totally extracted from the questionnaire records for the mean values. The activity level is designed to be seated quiet with the factor 1.0 of physiological diversities which is similar with the respondents' status in questionnaire survey (field study). The occupancy activity schedule is one of most important input for housing simulation work, which has strong relationship with indoor energy consumption and indoor thermal environment reaction. In this study the occupancy activity is not the research emphasis of living habit, therefore the input data is the mean values of this two field study records. Although these are assumptions and were extracted from the questionnaire records, this is again subject to change in different case apartments. That is the limitation for the further study of occupancy schedule. The questionnaire response of occupancy activity schedule and input of mean values are listed following:

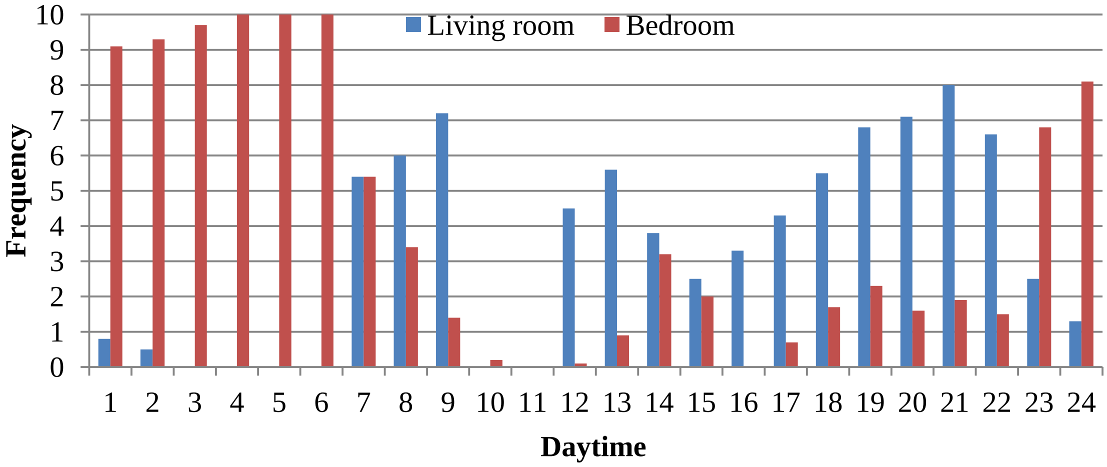


Figure 6.1 Occupancy activity schedule in case A

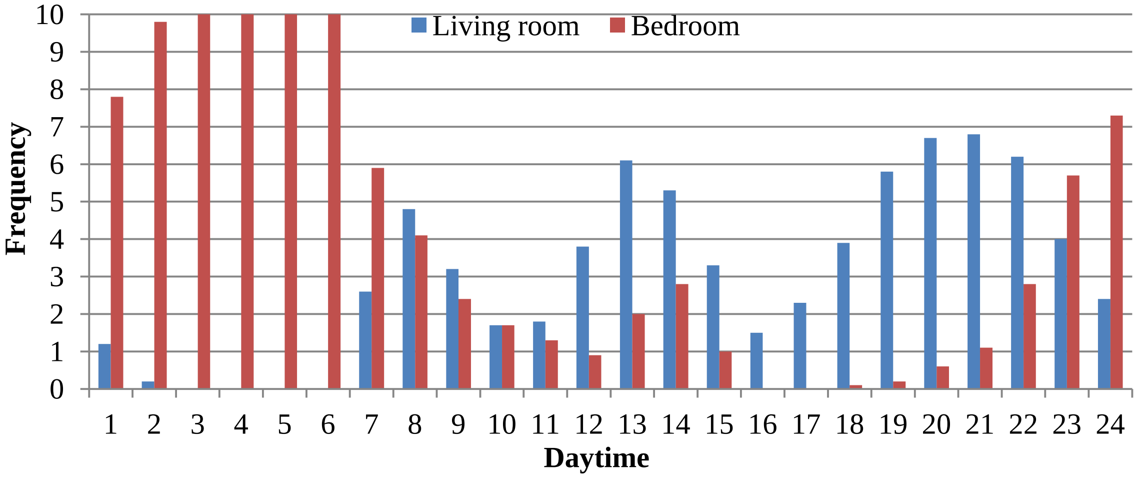


Figure 6.2 Occupancy activity schedule in case B

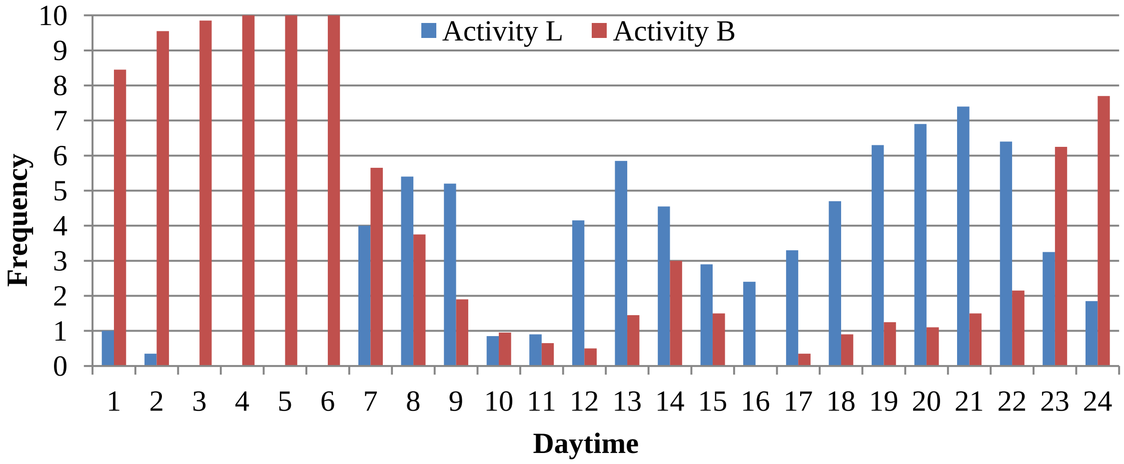


Figure 6.3 Occupancy activity schedule mean values for simulation input

6.3.4 LIGHTING SCHEDULE

The lighting is one of indoor heat gain source, and it is necessary use for daily life and considering for the simulation work. As the common setting of the simulation the general lighting energy is designed at 5.0W/m^2 for 100 Lux, the luminaries' type is designed as surface mount with radiant fraction of 0.72 and visible fraction of 0.18. It is common use in middle level of decoration home. The lighting energy would be calculated to effect the indoor heat balance and power use in the household energy consumption.

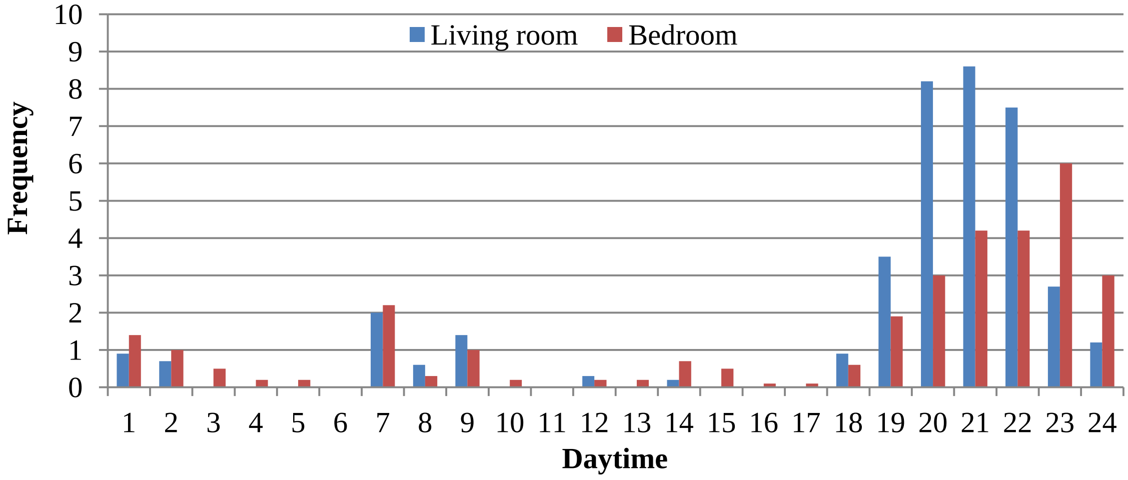


Figure 6.4 Lighting activity schedule in case A

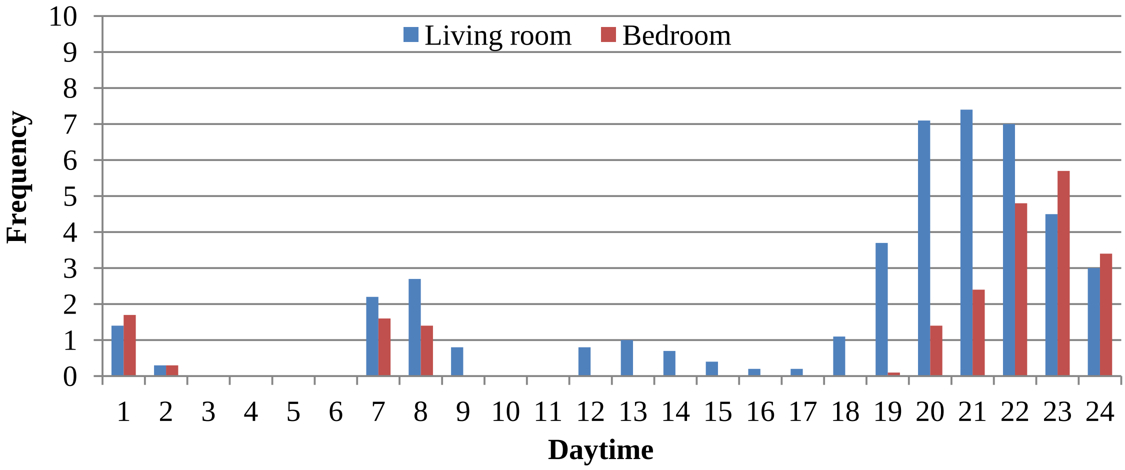


Figure 6.5 Lighting activity schedule in case B

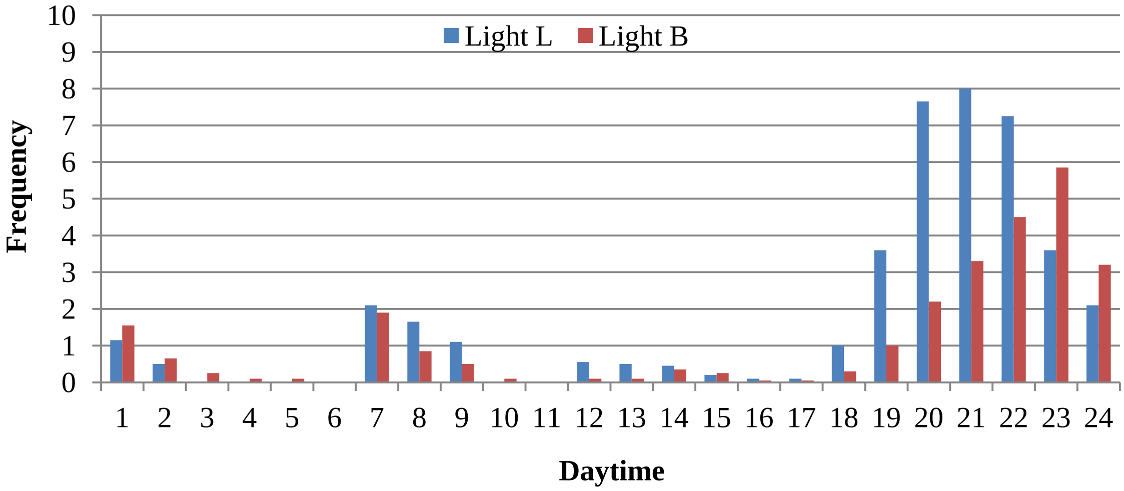


Figure 6.6 Lighting activity schedule mean values for simulation input

6.3.5 HVAC SETTING SCHEDULE

In this simulation work of DesignBuilder software the HCAC is key tab of heating or cooling simulation for indoor heat balance of thermal comfort and energy use. It is composed by six sub-points, namely are mechanical ventilation, natural ventilation heating, cooling, DHW and air temperature distribution setting. For the common China residential building the DHW is based on some small-power of thermal jug, different from the domestic boiler of DHW used in Europe country. There is no mechanical ventilation system for common China residential housing, and supporting with natural ventilation for indoor fresh air change. The device of heating and cooling is mainly design as fan coil unit for modelling split air conditioner use. Therefore the designing fuel is electricity from grid without preheating or precooling time. For the HVAC there are two types of calculation arithmetic one is simple way and the other is compact way. The first one is a kind of HVAC system defined by using plant seasonal efficiency data and modelled outside EnergyPlus, and the compact way is parametrically defined within EnergyPlus using compact HVAC descriptions. In this study the simulation work is based on the simple way of HVAC that means the heating or cooling system is modelled using basic loads calculation algorithms account for zone temperature set-points, ventilation requirements and hot water consumption rates (not including in this study). The HVAC input is activity-related data which will typically already be set up correctly in 'Activity' tab. The following figure represents the software interface of HVAC edition.

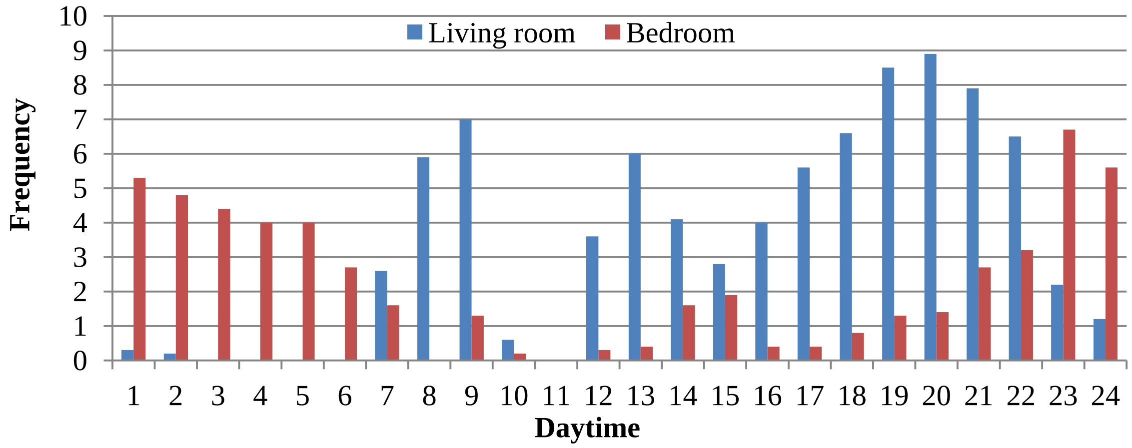


Figure 6.7 HVAC schedule in case A

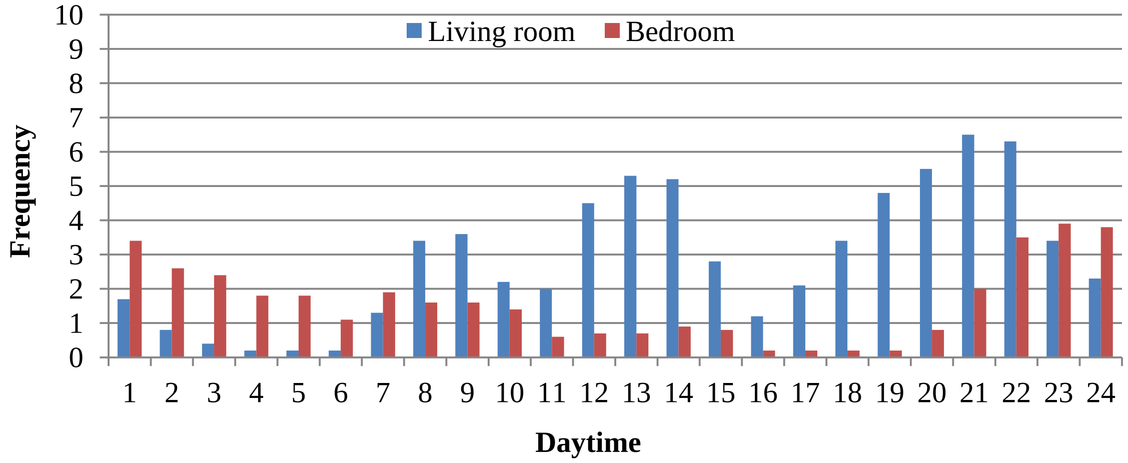


Figure 6.8 HVAC schedule in case B

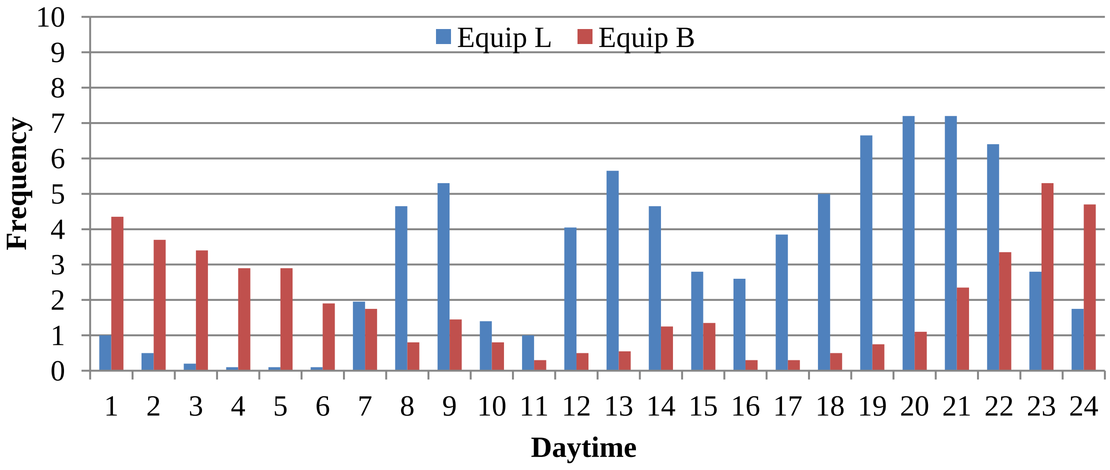


Figure 6.9 HVAC schedule mean values for simulation input

6.3.6 SIMULATION TOOL

Table 6. 4 The comparison between DesignBuilder and other four energy simulation packages

Software	Developer	Weather data	Advantage	Weakness
DOE-2	US, Lawrence Berkely National Laboratory	Input weather data document	Powerful and detail output	Difficulty in handle
EnergyPlus	US, Lawrence Berkely National Laboratory	Input weather data document	Powerful and accurate calculation	Difficulty in handle
DesignBuilder	UK, DesignBuilder	Input weather data document	Powerful and accurate calculation with friendly software interface	Hardly simulate for complex HVAC
DeST	China, Tsinghua University	'Medpha' weather model	Staged simulation for different phase design, with easy operation	Real-time Meteorological Data
PKPM	China, China Academy of Building Research Architectural Design Institute	Unknown	Gearing with current energy saving standard and easy operation	Low accuracy

The DesignBuilder is a state-of-the-art software tool for simulating building energy, CO2, lighting, and thermal-comfort performance checking. It can produce rapid 3-D modelling and includes a state-of-the-art dynamic energy simulation engine. It was designed by a British company named ‘DesignBuilder’ worked with the popular simulation engine of EnergyPlus designed by United States’ Department of Energy. It has very friendly software interface for architect, HVAC engineer, and energy consultant company and also research institution of university. It can be used in every step of building project, moreover the simulation result could provide performance data to evaluate and improve the building in its life circle. For the last version, there are five modules: (1) visualization—OpenGL (2) Simulation—EnergyPlus which two modules are basic tab for this software package. (3) HVAC—detailed EnergyPlus HVAC simulation (4) CFD—wind environment design (5) Daylighting design. It is easy to use and allows rapid modelling of complex buildings by non-expert users. One can easily input construction data, building HVAC, the lighting design and usage patterns based on activity schedules to calculate the heating or cooling designs and to simulate study of variant testing durations (for example, atypical summer/winter week, or the whole summer/winter). The model of DesignBuilder should be defined by the data input, and it is organised in a hierarchy, the default data of which is inherited from the level above in the hierarchy. The output of graphs and tables can be exported for in further statistical study. As the input of activity schedule, the simulation time-step was based on the questionnaire survey from field study, and it was designed as hourly in this study. The output simulation time-step is multi-optional. It was designed as daily for thermal comfort study and monthly for study of energy consumption. Based on table 6.4, we can find the DesignBuilder is an powerful and accurate calculation software for energy simulation work, and it also has friendly software interface. Although it is hard to do the work for complex HVAC it is not the main point in this PhD research.

6.4 INDOOR THERMAL COMFORT PERCEPTION

In this study, building performance is assessed using the subjective perception of the thermal environment and the objective energy consumption. The simulation manufacturer, DesignBuilder, presents the thermal environment prediction with ‘Pierce PMV SET’, which is based on the Pierce two-node model (Gagge and Nishi 1977; Gagge et al. 1986; Stolwijk and Hardy 1977). It is an extension of the research used for Fanger’s PMV-PPD model, taking advantage of the ability to compare thermal conditions between different environments (Djongyang et al. 2010). Figure 6.10 and Figure 6.11 are drawn from the Pierce PMV SET annual values in case A and B. According to the perception values in case A, nearly all cooling perception assessments are higher than -0.5 (the middle point between the neutral point of a comfortable ‘0’ and a slightly cool ‘-1’) in the high level of the ‘acceptable’ range, and the warming perception assessment is partly over 1.0 (slightly warm) and some of the assessments even reach approximately 2.0 (warm) in the later summer time. Comparing the detailed data across these three scenarios, during the cold winter the perception values of the second scenario are always close to the neutral point of zero level, and the perception values of the first and third scenarios are nearly the same as one another and are both lower than that of scenario two during cold conditions. During the hot summer, the values of the first and second scenarios are the same and are much higher than that of the third scenario. However, in case B the perception values of the three scenarios have a different representation than that of case A. During the cold winter the three scenarios each have a clearly respective perception tendency: the second scenario leads to the highest tendency (all higher than -0.5); the first scenario leads to the lowest tendency (all lower than -0.5); and the third scenario issomewhere here between the two (around -0.5). During the hot summer, the perception value is almost the same for the three scenarios, and the perception values are partly over the comfort range (0-1.0), reaching a value between 1.0 and 1.5.

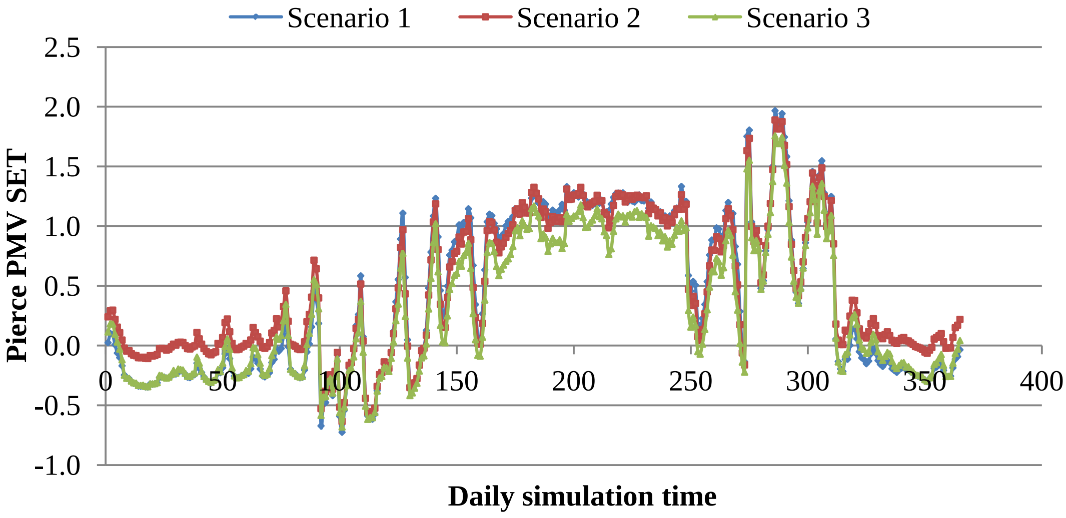


Figure 6.10 The pierce PMV SET results of case A with three scenarios

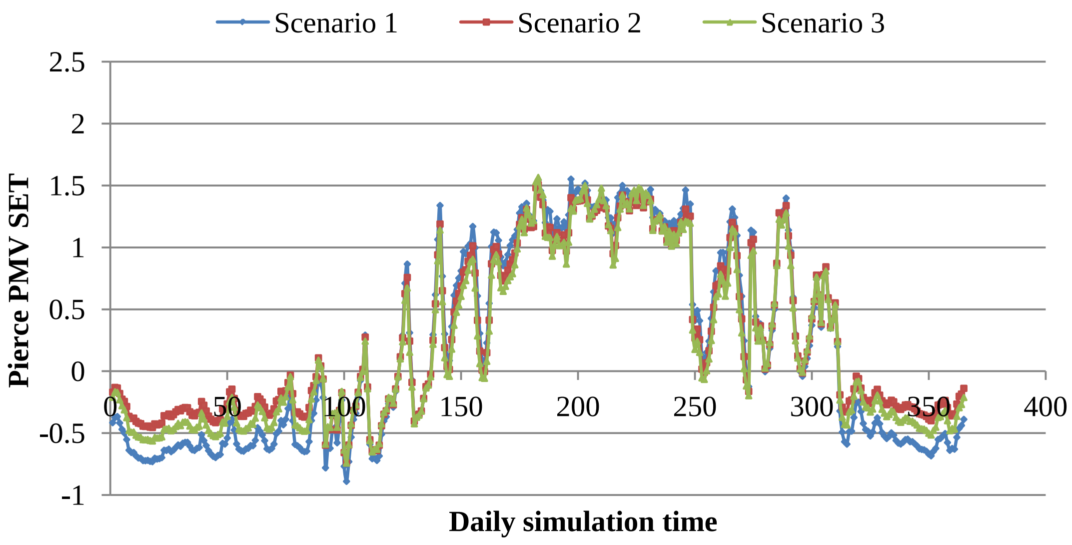


Figure 6.11 The pierce PMV SET results of case B with three scenarios

The results mentioned above indicate that the varying building layouts make a significant difference to the indoor thermal sensation. In case A the scenario of adaptive thermal comfort control results in an environment sensation which is close to the first scenario but lower than the second scenario during the cold winter. In the summer the adaptive thermal comfort controls of the third scenario result in an indoor thermal sensation which is cooler than that of both the first and second scenarios. Moreover, there are few perception values which fall over the acceptable upper limit (PMV-1.0). For case B, the third scenario of adaptive thermal comfort adapts effectively in winter, but has a very limited affect during the summer. In the cold winter the adaptive approaches result in an indoor perception that is warmer than energy-efficiency controls recommend and cooler than the ‘healthy housing’ standard. In the summer time the three scenarios of indoor thermal environment control result in similar indoor perception values. Although an extremely warm perception in summer time did not exist for case B, the perception assessment of a warm season is higher than the acceptable upper limit (1.0) of the PMV range. The winter perception assessment of case B is lower than that of case A. This shows that the adaptive thermal comfort investigation has different limitations according to the varying building-layouts. Comparing this with the current designing standard, the adaptive thermal comfort approach presents a higher cooling demand during the hot summer and a higher tolerance capacity during the cold winter in the prototype of case A. For case B, the adaptive thermal comfort approach presents similar perception results as the current Chinese thermal design standards for summertime. For winter, adaptive approaches make a medium level of thermal perception.

6.5 ENERGY CONSUMPTION PERFORMANCE

In this study, the simulation of energy consumption performance included lighting use and energy for heating and cooling. The research is based on the energy consumption per unit of indoor floor area, and presents the energy efficiency with the diversity of building prototypes. The energy usage only takes into account electricity, and the energy consumption is only broken down for heating, cooling and lighting use. Because the fuel consumption of electricity will not account for all energy usage, the system load multiplies the CoP value. The CoP value is defined as 3.5 stands for the system efficiency rate for this zone's levels of heating and cooling. Thus the heating system Coefficient of Performance (CoP) is used to calculate the fuel consumption which is required to match the indoor environment load. The energy use resulting from lighting is almost a constant output due to the use of communal indoor-space lighting.

Tables 6.5, 6.6 and 6.7 present the monthly energy consumption for lighting, heating and cooling in case A with different scenario results. We can find that the peak value of energy usage usually takes place in summer time and there are times when there is an extra demand for indoor heating or cooling before or after particularly extreme seasons of summer and winter (June, July and August are typically defined as summer, whilst December, January and February are typically defined as winter). According to the monthly energy breakdown for lighting, heating and cooling, and the indoor energy used per unit of floor area, the first scenario of energy efficiency has the lowest results, and the second scenario of healthy housing standard has the highest costs, whilst the scenario of the adaptive approach had medium levels of energy costs. They (34.05kWh/m^2, 40.14kWh/m^2 and 37.77kWh/m^2) are much lower than the recommended energy use for heating and cooling in Yichang city where the power consumption indicator is 51.4kWh/m^2. According to the breakdown of energy use in case A, the energy use for cooling is always higher than the energy use for heating. 65% of energy consumption is caused by cooling under the first scenario, 56% for cooling under the second, and 66% under the thirds scenario. This means that the current housing design standard (energy efficiency and healthy housing) underestimates the energy use for cooling and overestimates the energy consumed by heating than that of the adaptive thermal comfort study in case A.

Table 6.5 The energy breakdown of case A in scenario 1

Monthly	**Lighting**	**Heating**	**Cooling**	**Total**	**Usage per indoor space-HVAC control**
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh/m^2)
January	57.55	478.25	0.00	535.80	4.13
February	51.98	344.02	0.00	396.00	2.97
March	57.55	185.39	0.00	242.94	1.60
April	55.69	0.06	6.68	62.43	0.06
May	57.55	0.00	130.76	188.31	1.13
June	55.69	0.00	478.50	534.19	4.13
July	57.55	0.00	832.63	890.17	7.19
August	57.55	0.00	819.83	877.38	7.08
September	55.69	0.00	266.42	322.11	2.30
October	57.55	0.00	18.26	75.81	0.16
November	55.69	83.04	3.00	141.73	0.74
December	57.55	295.93	0.00	353.48	2.56
Annual	677.59	1386.69	2556.08	4620.35	34.05 11.97 for heating 22.08 for cooling

Table 6.6 The energy breakdown of case A in scenario 2

Date/Time	**Lighting**	**Heating**	**Cooling**	**Total**	**Usage per indoor space-HVAC control**
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh / m^2)
January	57.55	618.79	0.00	676.34	5.34
February	51.98	469.71	0.00	521.69	4.06
March	57.55	302.68	0.69	360.92	2.62
April	55.69	18.75	17.22	91.66	0.31
May	57.55	2.76	170.21	230.52	1.49
June	55.69	0.00	488.49	544.18	4.22
July	57.55	0.00	794.54	852.09	6.86
August	57.55	0.00	787.49	845.04	6.80
September	55.69	0.16	293.44	349.30	2.54
October	57.55	14.21	41.60	113.35	0.48
November	55.69	186.56	7.35	249.61	1.67
December	57.55	433.77	0.00	491.31	3.75
Annual	677.59	2047.40	2601.04	5326.02	40.14 17.68heating 22.46cooling

Table 6.7 The energy breakdown of case A in scenario 3

Date/Time	**Lighting**	**Heating**	**Cooling**	**Total**	**Usage per indoor space-HVAC control**
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh / m^2)
January	57.55	474.76	0.00	532.31	4.10
February	51.98	342.94	0.00	394.91	2.96
March	57.55	207.09	1.56	266.19	1.80
April	55.69	15.92	47.04	118.65	0.54
May	57.55	2.48	229.74	289.77	2.01
June	55.69	0.00	540.77	596.46	4.67
July	57.55	0.00	818.77	876.32	7.07
August	57.55	0.00	813.04	870.59	7.02
September	55.69	0.17	347.97	403.84	3.01
October	57.55	12.34	82.79	152.68	0.82
November	55.69	116.85	16.59	189.13	1.15
December	57.55	303.37	0.00	360.92	2.62
Annual	677.59	1475.92	2898.28	5051.78	37.77 12.74 for heating 25.03 for cooling

Tables 6.8, 6.9 and 6.10 present the simulation results of case B. As with case A, extra energy is required for the cooling and heating of buildings before or after extreme seasons (both summer and winter). The peak value of energy use for cooling during summer is similar to that for heating during winter in case B. The energy use for indoor cooling is close to the usage for indoor heating requirements within all three scenarios. They are 49%, 54% and 51%, respectively. It indicates that in case B, the adaptive thermal comfort approach provides a medium level of energy use for both building environment cooling and heating. The first scenario provides the lowest energy consumption per unit of indoor floor area and consequently would receive the lowest electricity bill. The second scenario results in the highest energy use and consequently the priciest bill. Finally, the third scenario’s results are similar to those found in the second scenario.

Table 6.8 The energy breakdown of case B in scenario 1

Date/Time	**Lighting**	**Heating**	**Cooling**	**Total**	**Usage per indoor space-HVAC control**
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh / m^2)
January	45.50	372.60	0.00	418.10	3.87
February	41.10	272.36	0.00	313.46	2.83
March	45.50	154.08	0.00	199.58	1.60
April	44.03	0.22	0.05	44.30	0.00
May	45.50	0.00	26.39	71.89	0.27
June	44.03	0.00	209.26	253.30	2.17
July	45.50	0.00	409.82	455.32	4.25
August	45.50	0.00	405.90	451.40	4.21
September	44.03	0.00	105.69	149.72	1.10
October	45.50	0.01	2.90	48.41	0.03
November	44.03	74.52	0.28	118.84	0.78
December	45.50	238.50	0.00	284.01	2.47
Annual	535.76	1112.29	1160.29	2808.34	23.58 11.54 for heating 12.04 for cooling

Table 6.9 The energy breakdown of case B in scenario 2

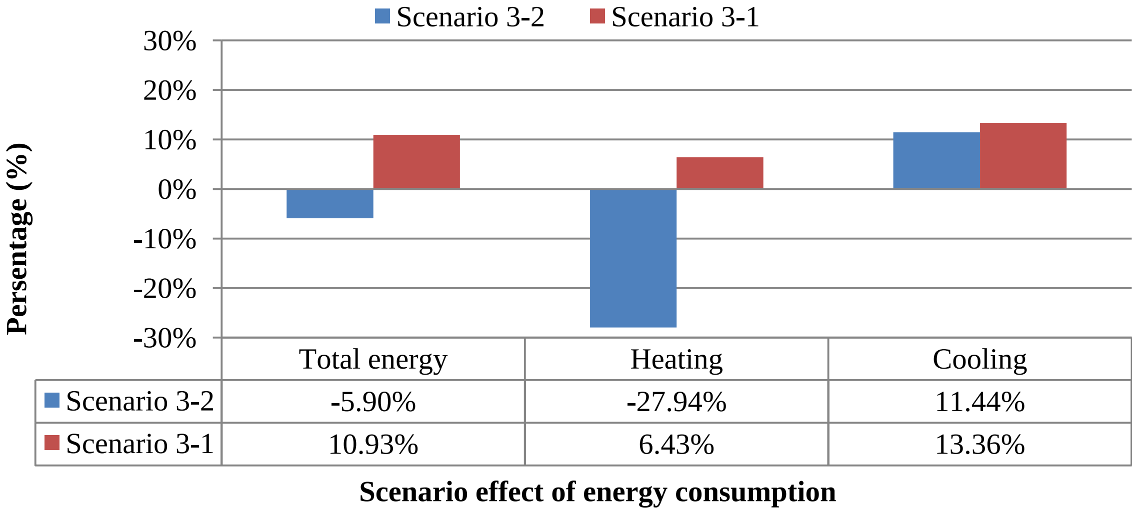
Date/Time	**Lighting**	**Heating**	**Cooling**	**Total**	**Usage per indoor space-HVAC control**
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh / m^2)
January	45.50	474.47	0.00	519.98	4.92
February	41.10	363.01	0.00	404.11	3.77
March	45.50	241.44	0.51	287.45	2.51
April	44.03	20.58	4.77	69.39	0.26
May	45.50	1.84	67.54	114.89	0.72
June	44.03	0.00	251.91	295.94	2.61
July	45.50	0.00	437.60	483.10	4.54
August	45.50	0.00	428.91	474.41	4.45
September	44.03	0.05	146.93	191.02	1.53
October	45.50	10.50	11.03	67.03	0.22
November	44.03	153.91	0.60	198.54	1.60
December	45.50	338.01	0.00	383.51	3.51
Annual	535.76	1603.81	1349.80	3489.37	30.65 16.64 for heating 14.01 for cooling

Table 6.10 The energy breakdown of case B in scenario 3

Date/Time	Lighting	Heating	Cooling	Total	Usage per indoor space-HVAC control
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh / m^2)
January	45.50	417.91	0.00	463.41	4.34
February	41.10	316.35	0.00	357.45	3.28
March	45.50	207.30	0.39	253.19	2.16
April	44.03	25.95	10.41	80.40	0.38
May	45.50	4.11	90.24	139.85	0.98
June	44.03	0.01	253.60	297.64	2.63
July	45.50	0.00	407.94	453.44	4.23
August	45.50	0.00	400.04	445.54	4.15
September	44.03	0.29	161.61	205.93	1.68
October	45.50	16.87	24.70	87.07	0.43
November	44.03	127.51	3.22	174.76	1.36
December	45.50	291.29	0.00	336.80	3.02
Annual	535.76	1407.58	1352.13	3295.47	28.64 14.61 for heating 14.03 for cooling)

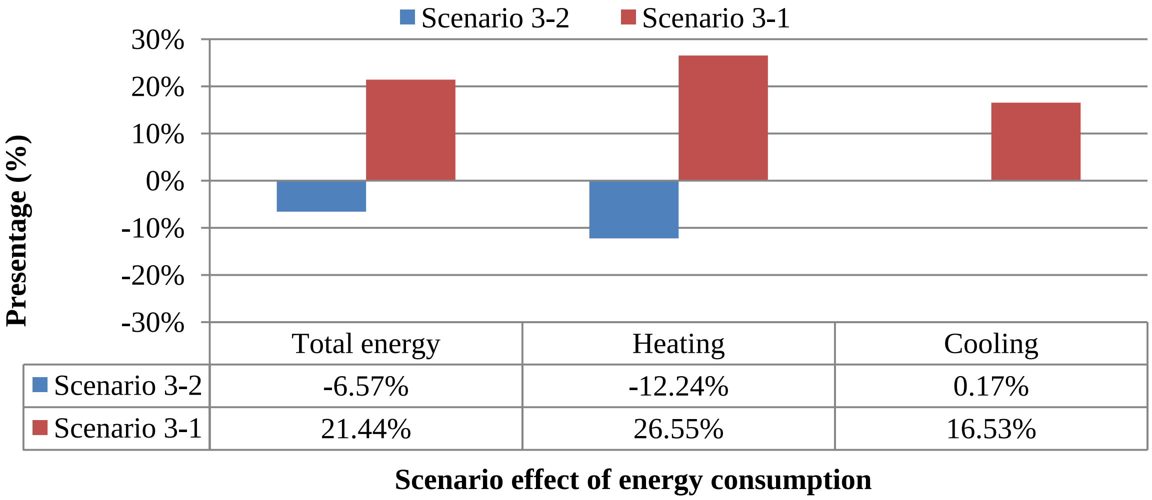
Figure 6.12 and Figure 6.13 present the compared results of energy use per unit of flooring for heating and cooling, and the total consumption of energy in each case study between each scenario of environment control. For the energy consumption study of simulation work, case A has greater energy use for cooling during summer and some extra cooling energy use takes place before or after this season. Energy expended on heating is less than that of cooling and, similarly, extra energy is used on heating before or after the winter. In case B, the energy use for cooling and heating are quite similar. The energy uses per unit of indoor floor area are both lower than those of case A. When comparing these three scenarios, it can be found that the scenario of adaptive thermal comfort input could save 6.0-6.5% of energy consumption than that by applying the current healthy housing design standard in China. However, it would raise by 11.0-21.5% the energy use than that if applying the current design standard for energy efficiency of residential buildings in a HSCW zone. Comparing the current healthy housing standard in China, the adaptive thermal comfort approaches greater reduces energy use from heating in case A (-27.94%) than that of case B (-12.24%). However, the amount of energy required for cooling would have a greater increase in case A (11.44%) than it would in case B

(0.17%). Comparing the current energy efficiency design standard for residential buildings in a HSCW zone, the adaptation environment control results in a 6.43% increase in heating energy use in case A and 26.55% in case B. The cooling energy use would increase to 13.36% in case A and 16.53% in case B.



	Total energy	Heating	Cooling
🟦 Scenario 3-2	-5.90%	-27.94%	11.44%
🟥 Scenario 3-1	10.93%	6.43%	13.36%

Figure 6.12 The comparison of per unit floor area energy consumption for heating and cooling in case A with different scenarios of environment control



	Total energy	Heating	Cooling
🟦 Scenario 3-2	-6.57%	-12.24%	0.17%
🟥 Scenario 3-1	21.44%	26.55%	16.53%

Figure 6.13 The comparison of per unit floor area energy consumption for heating and cooling in case B with different scenarios of environment control

6.6 SUBJECTIVE PARTICIPATION FOR BUILDING THERMAL PERFORMANCE

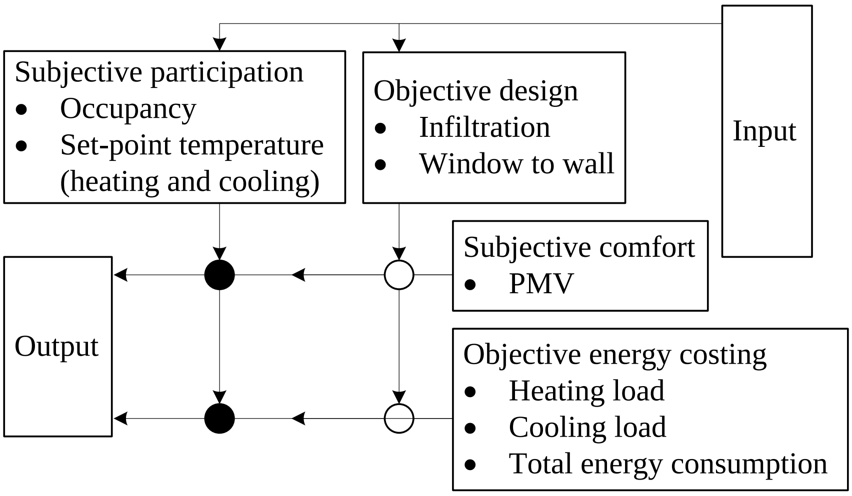


Figure 6.14 The framework of building thermal performance input and output

In this study section of the, Figure 6.14 presents a clear framework of the building thermal performance concept, which indicates that both objective building design factors and subjective people-participation are related with subjective comfort and objective energy costs. As we know, the objective building design is the key point for a building's level of heating or cooling consumption and, in the HSCW zone of China, the energy consumption calculation is usually based on the steady-state heat transfer model (Xiuzhang Fu 2002b) and a simplified calculation method has been proposed in related national designing standards for energy efficiency. The subjective participation is a kind of extension of the research which applies the adaptive thermal comfort theory; it takes into consideration the actual personal thermal sensation and the adaptive mechanism used (psychological and behavioural). The occupants have a demand for thermal environment control which can be predicted using regional weather conditions for the improvement of a building's thermal performance. In this study, the building infiltration and the ratio of the external windows area are designed as two factors which are related to residential energy use for heating up and cooling down, and therefore these two parameters are defined as the objective design input. In this simulation work the subjective output is Fanger's PMV model of thermal comfort and the objective output is the energy costing of the zone's heating/cooling load and the total energy consumption. Figure 6.15shows the modeling image of the building and block.

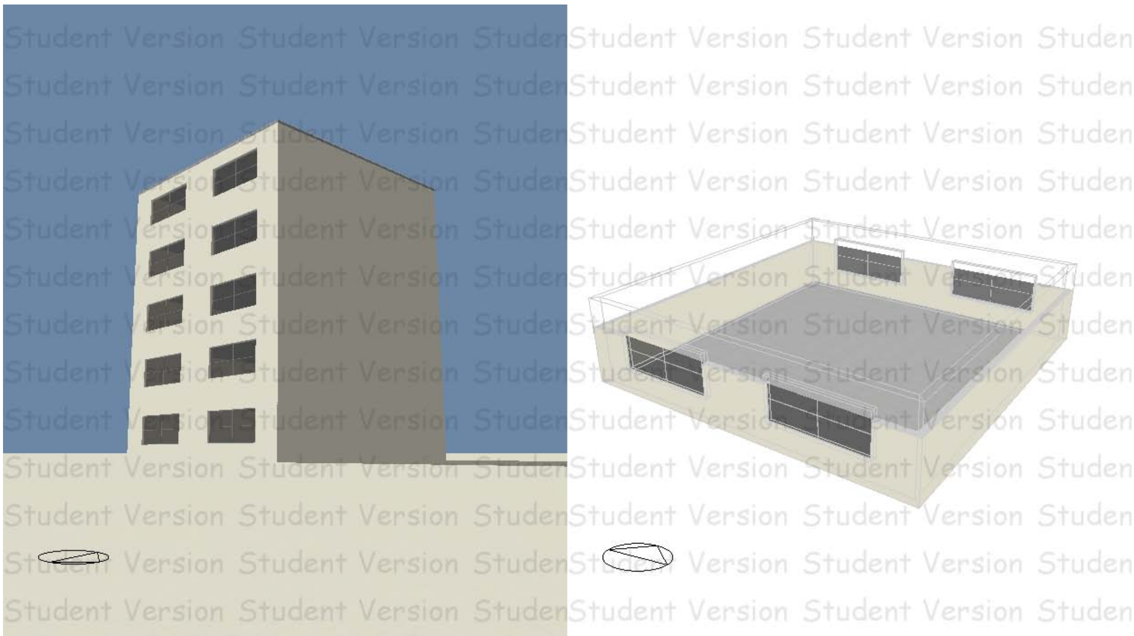


Figure 6.15 The visualising image of square shape model

The typical field study on building performance and energy consumption is almost always based on the building material, the structural elements of the property and so on. The occupants' participation affects the building unit use and their thermal environment perception. The occupants' participation is an important and significant area of research, and includes occupants' behaviour adaptation and any psychological impact. Therefore in this simulation study the influence coefficient is defined by the parameters of occupancy density and the optional thermal environment control of set-point indoor air temperature (cooling and heating). Because of the limitations of the DesignBuilder software, the activity tab is composed of the occupants' activity schedule, occupancy density and the related template of the indoor environment control without taking into consideration any parametric model of anthropological characteristics or social background information. Consequently, the subjective people-participation is designed with variant levels of indoor people density.

The simulation work of a square shaped model is based on the inputs of objective design and subjective participation. The external envelope structure and HVAC system are similar with the former simulation study for case A and case B listed in Table 6.11. In this part of the simulation study, the lighting effect is ignored and the objective block is marked on the middle unit. There is no consideration of heat transfer between floors. The simulation work is a parametric analysis, which is created by DesignBuilder. The aim is to understand how a building's thermal performance is affected by variations of objective and subjective parameters.

Table 6.11 Simulation input of square shape model

Simulation input	**Construction**	**Value**	**Note**
Objective design	external wall	0.946	U-value
	Internal wall	2.061	U-value
	Internal floor	2.237	U-value
	External window glazing	1.761	U-value
	Window to wall rate	0-100%	-
	Infiltration	0-1.4	Airtightness
	HVAC heating/cooling CoP	3.5	-
Subjective participation	Occupancy density	0/0.2/0.4/0.6	people/m^2
	Heating set-point temperature	16/18/20	℃
	Cooling set-point temperature	24/26/28	℃

As the presentation of simulation processing the output is parametric analysis. First of all the Figure 6.16 indicates the relationship between Fanger's PMV and the rate of window to wall and building infiltration under the effect of indoor occupancy density. According to the top part the of image, if the percentage of the window to wall ratio increases from 0 to 100%, Fanger's PMV indoor thermal perception index is gradually warming up, and regardless of the window ratio to wall, there is not a big difference between each level of occupancy density. The bottom image of Figure 6.16 shows the infiltration design of PMV simulation alongside the effect of occupancy density. The infiltration of airtightness design has a negative effect for the Fanger PMV. Thus the value of Fanger PMV decreases with the increasing of infiltration ratio, moreover the reduction ratio is gradually increasing with more people participation of indoor density. For example when the occupancy density is zero the infiltration reduction is not over 0.3 PMV units, however when the occupancy density is at the point of 0.6 the reduction ratio is about 0.9 PMV units.

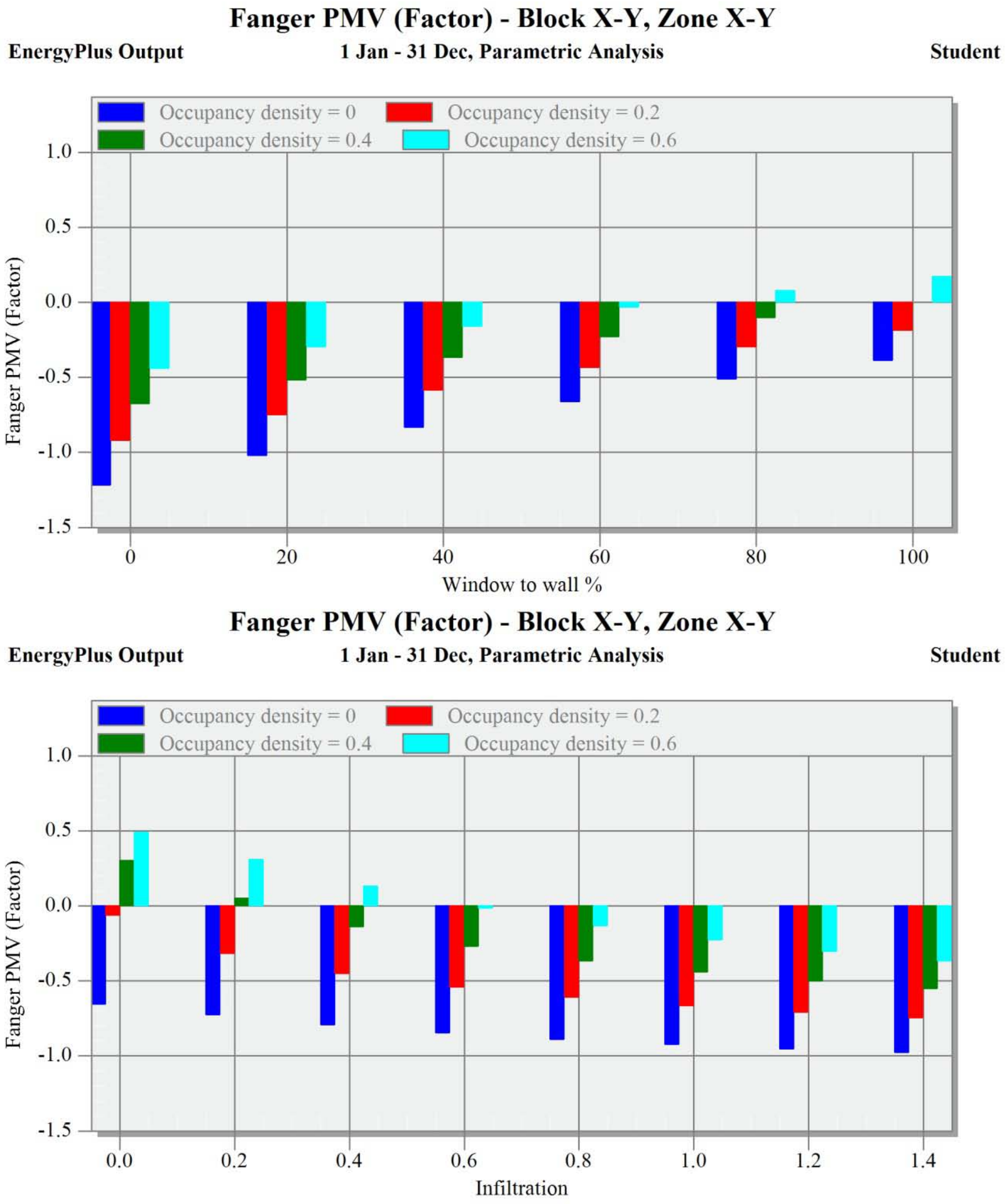


Figure 6.16 The relationship between Fanger PMV and rate of window to wall and building infiltration under the effect of indoor occupancy density

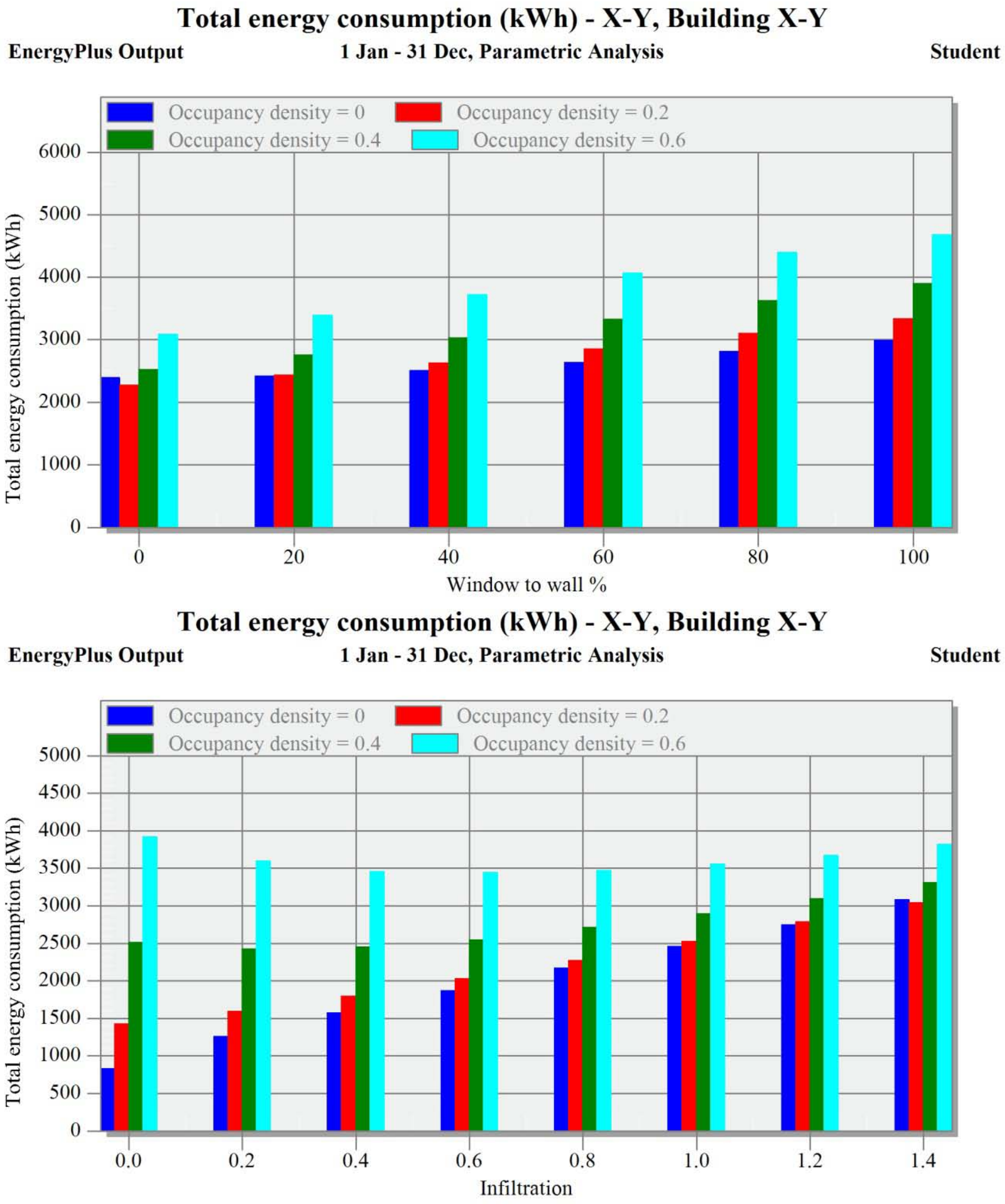


Figure 6.17 The relationship between total energy consumption and rate of window to wall and building infiltration under the effect of occupancy density

Figure 6.17 displays the relationship between the total energy consumption and the rate of window to wall ratio and building infiltration under the effect of occupancy density. The subjective participation of occupancy density is designed at different levels and it is found that a significant influence exists in the increasing rate of energy consumption caused by increasing infiltration. Generally, the higher the level of people density, the higher the total energy use, and the deviations of energy use between different levels of occupancy density tend to increase as the size of the window area increases. The deviations of energy use tend to decrease with the rising values of infiltration design. In the graph showing the relationship of the window to wall ratio, the total energy consumption appears almost as a straight line, but in the lower part of the diagram the trend line of energy use under the higher and lower occupancy densities has a more obvious hyperbolic curve.

6.7 BUILDING SHAPE COEFFICIENT QUERY FOR BUILDING THERMAL PERFORMANCE

In China the building shape coefficient is a key factor of building design standards in energy efficiency studies. For example, in China, the first energy saving standards which concerned buildings focused on central heating in buildings built in the north of China: ‘Energy conservation design standard for new heating residential buildings’ (JGJ26—86) and its later visions of JGJ26-95 JGJ26-2010, and the newest energy saving regulation for civil buildings within the HSCW zone is JGJ134-2010 (Heldenbrand 1974) all present mandatory definitions of the building shape coefficient. It is defined as a ratio of a building’s outer surface area (which contacts external air) to its inclusive volume. The formal equation is named that:

$$\mathrm{S} = \mathrm{F}_0/\mathrm{V}_0 \text{ (Equation 6-1)}$$

S means ‘building shape coefficient’;

F_0 means surface area of building external envelop contacted outside air ;

V_0 means building volume wrapped by building external envelop which contacts outside air;

Based on the ‘building shape coefficient’ definition, the surface area to volume ratio is its basic concept used in physics, chemistry and biological area. By using in architectural research, huge body of building is usually supposed to get small coefficient of building shape and small building is on the contrary. In fact, the building shape scaling does not have linear relationship with its coefficient change. In China HSCW zone building design standard (JGJ 134-2010 mentioned in Chapter 2 section 2.7) defined that under the same other conditions the building energy consumption could be more within higher building shape coefficient designing context. Actually a building shape coefficient is often over the standard control in practical building design, especially happened in China booming building market. Moreover a building design should be judged by its maintaining performance of energy use and comfortable environment.

According to the related research published in the USA and the UK, the building shape coefficient is not mentioned as a determining factor for energy conservation. Since 1974 the first energy conservation design standard and evaluation criterion in the world which relates to buildings - NBSIR 74-452 - was published by the National Bureau of Standards (NBS), and based on this report the American Society of Heating Refrigerating and Air-conditioning Engineer published a series of reports of ASHRAE 90. These professional publications simply do not emphasize the index of a building’s shape as an effective method to limit or reduce energy use in buildings.

Simulation software provides an easy way to think about the relationship between energy consumption and building shape coefficient. According to the related studies concerning China’s building shape coefficient, the lowest building shape coefficient is the square. Consequently, the simulation shape is defined as a square shape of cross section: a square area of 12 meters by 12 meters. The total height of the modelling block (see Figure 6.18) is designed as 18 meters, which is approximately equal to a six-floor height building (a common type of Chinese low-rise residential building). The floor-to-floor height change is from 3 meters to 18 meters (3m, 3.6m, 4.5m, 6m, 9m, 18m), thus the number of floor levels is accordingly altered from six floors to one. It is defined as a changing variable for the differing energy performance. The external window area is designed to be at a constant setting of 30% glazing on the external wall. There is no lighting settled in the simulation and the HVAC setting is designed as the input of simulation work. The output will indicate the relationship between the energy used for heating and cooling and the varying heights of the buildings’ storeys, and the relationship between the energy use per unit of indoor floor area and the storey-height’s varying designs.

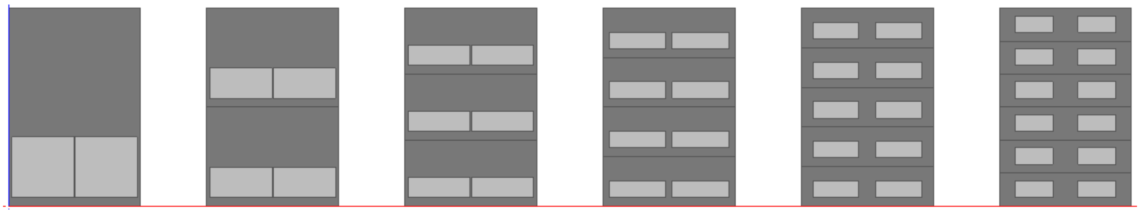


Figure 6.18 The image of simulation work for energy consumption under the same building shape coefficient

The simulation of 9x9m, 12x12m and 15x15m square block models respectively stand for small, medium and large apartments. As studies of the relationship between building shape coefficient and energy conservation developed by the China professional society demonstrate (Cao et al. 2005; Xiangzhao Fu 2002a; X. Liu and Ding 2006; Xiao 2004) it is agreed that a common view of building shape coefficient is a significant factor in a building's energy consumption levels. A larger building shape means more energy consumption may be required to maintain a comfortable indoor thermal environment.

In this simulation study, all the building blocks are the same height of 18m. Figure 6.19 demonstrates that the total energy consumption of the building block has a tendency of decreasing at first, but increases as the height of the building increases with each storey. The larger crossing section block has a larger size of modelling block, which has a relatively lower building shape coefficient and a higher total energy consumption. Figure 6.20 presents the energy use per unit of indoor flooring within the different designs of buildings based on their storey height. We can find that all of their relationships are linear, and a block that has a higher storey height with fewer storey levels always has a higher energy consumption per unit of floor area in each modelling block. Moreover, in regards to variant building blocks with identical storey-level designs, the block that has a larger crossing section area has lower energy use than others with a smaller crossing section. Figure 6.21 presents the relationship between energy consumption per unit of floor area and the ratio of the superficial area and the actual floor area. All of their relationships are linear, and the higher the ratio, has greater the amount of energy consumed. According to the situation of same ratio, the block that has a larger crossing section area uses more energy.

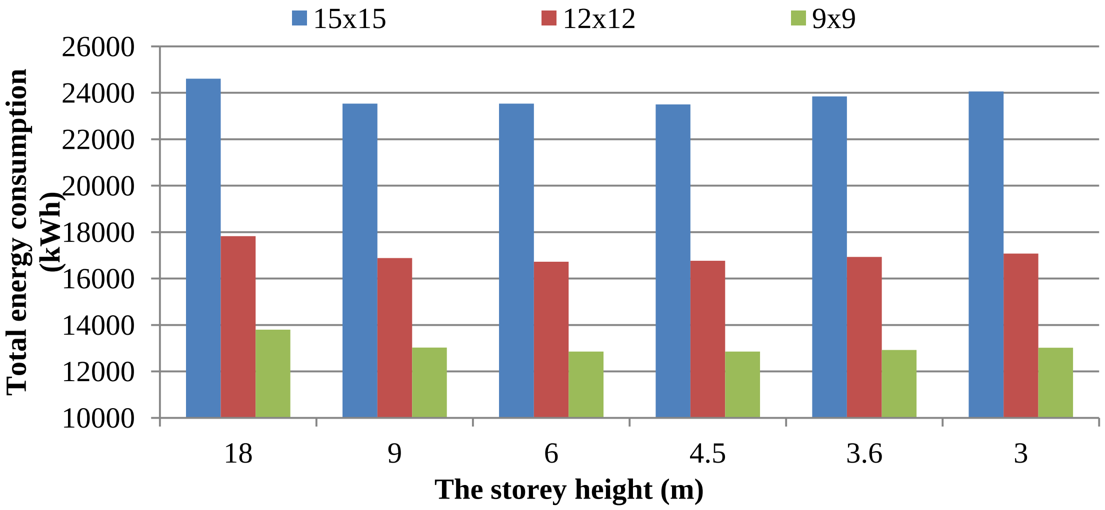


Figure 6.19 The relationship between the total energy consumption and building storey height under different size of model

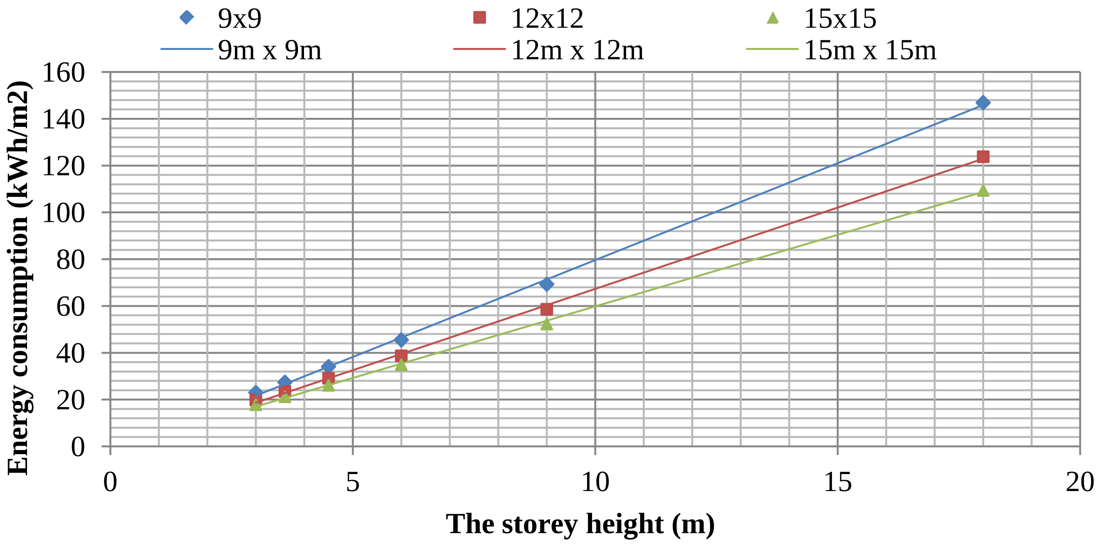


Figure 6.20 The relationship between energy consumption in unit floor area and the storey height

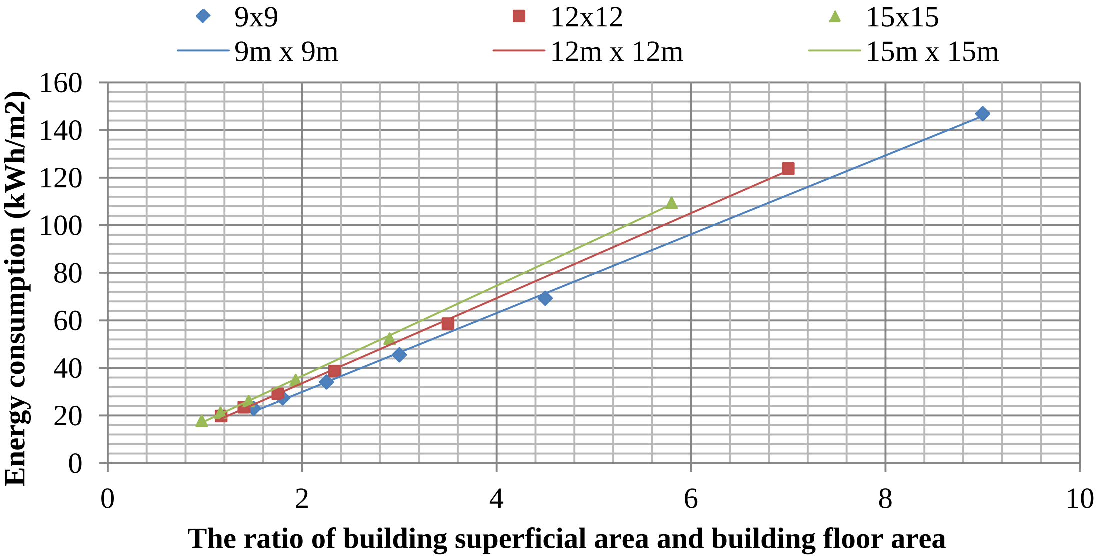


Figure 6.21 The relationship between energy consumption in unit floor area and the ratio of building superficial area and building floor area

Consequently, the building shape coefficient is a rough concept of parametric design for a building's energy conservation issues. Moreover, the design of an indoor floor area affects the level of demand for indoor energy consumption and a building's energy use performance. The total energy consumption has a parabolic function tendency as the indoor floor area increases (a constant building total height with different indoor storey level design). The building's performance of energy consumption per unit of flooring has a linear relationship with storey height design and the ratio of a building's superficial area and the actual building floor area. However, when the storey height design of these three blocks is the same, a larger cross-section area causes the building's energy performance to lower, and if the ratio of the building's superficial area and building floor area is the same, a larger cross-section area causes the building's energy performance to improve. In China, the current climate's regional standard of residential building design has a great shortage in the limitations of building shape design for energy conservation. The indoor space design has a strong link with thermal environment comfort requirements and current Chinese building shapes define the success of energy conservation by applying the building design limitations. For example, the energy efficient buildings are often designed as a boring box for matching the mandatory limitation of shape coefficient, for example the 0.4 and 0.35 for different shapes of building in a HSCW zone (MHURD-PRC 2010). In China, those who have undertaken related research (Cao et al. 2005; X. Liu and Ding 2006) tend to discuss the optimal building shape, the optimal storey levels and so on. They are usually a far cry from the reality of practical projects which deal with the energy efficiency research and building performance.

6.8 CONCLUSIONS

In this research, buildings' thermal performance is analysed using DesignBuilder, intelligent software which uses the powerful and comprehensive energy simulation engine EnergyPlus to simulate the thermal performance for indoor thermal comfort and energy issues. Firstly, three scenarios of indoor environment control were created to demonstrate how the adaptive thermal comfort approach has different effects in two selected cases. The secondary part of this research has tried to revise some misunderstandings of building design which are essential in China's regional designing standard. The current definition of building shape coefficient is an unsatisfactory index for thermal performance and energy efficiency issues in buildings in China. Thirdly, other simulation studies of buildings' thermal performance are also concerned with subjective people-participation and it is a method to extend the adaptive thermal comfort theory with the reasonable energy conservation research. The following conclusions can be drawn:

- According to the simulated output of the case study, applying three differing scenarios of indoor thermal environment control, HVAC settings and mixed modes of indoor thermal environment control will result in different success rates of a building's thermal performance. The adaptive thermal comfort strategy could present an effective way of measuring occupants' expectation of their thermal environment and might also provide improvement for indoor environment control with a positive balance between thermal comfort and energy efficiency. Case A - a long depth prototype with a Y-axis room combination - has a warmer environment during winter and an acceptable thermal perception during the hot summer, but there is a potential problem for an extremely hot thermal perception. Case B - a square prototype with an X-axis room combination - has an acceptable thermal perception during cold conditions and it is lower than that simulated in case A. However, warmer perception values are usually over the upper limit of the thermal comfort range in case B, even if there is no extremely warm perception, and the perception values are better than those of case A.
- The 'adaptive' approaches in this research indicate that China's current healthy housing standard underestimates the occupants' adaptive capacity for cold indoor situations whilst overestimating their capacity for hot indoor situations in both prototypes of cases. The energy efficiency standard totally overestimates occupants' adaptive capacity for all indoor thermal situations in these two cases. Regarding the difference between these two selected cases, the deviation of adaptive thermal comfort and China's current healthy housing

standard is more significant in case A. However, the deviation of the adaptive thermal comfort method and current energy efficiency standards for residential buildings in HSCW zones in China is more significant in case B.

- Issues of buildings' thermal performance need to highlight the limitations of objective building design and the current single-decision algorithm of building environment research should become a double-decision algorithm, with the addition of the subjective people-participation. The simulation results demonstrate that the subjective people-participation has a significant impact on a building's thermal performance.
- The relationship between building shape coefficient and energy saving is a fairly vague concept in the common idea of building energy consumption and so it is hard to say that a low building shape coefficient always has low energy consumption. For the building energy issues the thermal performance would be better defined by the energy efficiency per unit of indoor floor area. This is better than the current definition of building shape coefficient defined by the ratio of building superficial area and its covering volume. The ratio of superficial area of building external envelope to indoor floor area has a linear relationship with the building's energy performance.

CHAPTER 7 CONCLUSIONS

7

7.1 INTRODUCTION

This chapter presents a clear review of previous chapters on research procedure, findings, and methodology, and also expresses the limitations of this study and gives a perspective for future work. This section will refer back to the introductory chapter for getting answers to the research questions outlined there. Building thermal environment is an important design sector for indoor thermal comfort assessment and building energy consumption impact. Adaptive thermal comfort research provides more chance of subjective occupants' participation and provides a good understanding of actual people's cognition of thermal environment. Chinese residential building is going to start a transformation from rushing into quantitative building construction to qualitative improvement of building environment performance. This research has great significance for China's new building strategy as it is good to construct environment-friendly and energy-efficient residential buildings within China's special climatic zone.

7.2 RESEARCH PROCEDURE

A number of research methods were implemented in this PhD research based on subjective investigation and objective measurement. They aimed to fill the gap between rational thermal comfort empirical equations and actual occupants' indoor thermal environment perception. It is the first time that the 'black box' adaptive thermal comfort theory has been applied in a Chinese residential building study, and the first time that the current environment design scenarios for energy efficiency building and healthy housing have been compared with adaptive thermal comfort research. By using building energy performance ideas to validate the concept of adaptive thermal comfort, this was fruitfully applied to building environment design, especially in HSCW zone for defeating unbearable thermal potential in hot summer and cold winter. Different subjective and objective research methodologies were surveyed, some of which were applied in this research and are listed below.

First of all, the literature review mainly focused on two different parts of research orientation: one is concept derivation and the other one is field study. The review process provides a clear understanding of thermal comfort research's objectives and queries. More and more theoretical research carries out the queries of the current ASHRAE standard for thermal comfort range and static heart transfer of the PMV model. It presents a big challenge for actual indoor thermal comfort, and extensive research has been investigating further adaptive coefficient models and field studies within different weather situations. The comprehensive field studies mainly observe the application of ‘effective temperature’ (ET), standard ‘ET’ (SET) and adaptive thermal comfort theory in various climatic zones worldwide. These field studies favour an adaptive approach for occupants’ thermal sensation preferences. There are some sub-points of adaptive thermal comfort for physiological and non-physiological (psychological and behavioral) adaptation. The literature review gives an idea of the research direction of this PhD, which is investigating adaptive thermal comfort in Chinese residential building environments, and extending the subjective adaptive approach for the research of personal comfort perception preferences.

Secondly, case studies of two typical residential buildings is an effective investigation with specific objectives. Various Chinese residential buildings are based on these two prototypes of axial room space combinations. This research presented the divergence of the two different cases, and the detailed research of adaptive thermal comfort suggested the accuracy of an adaptive coefficient for analysing of indoor thermal sensitivity.

Thirdly, the field study included an on-site questionnaire and on-site measurements. This method of collecting subjective assessments of indoor thermal sensation (indoor thermal experience) and mean values of objective thermal parameters produces records that prepare for PMV model calculation. However, in the field study operation process, the pre-training is careful about psychological skewing. On the one hand the related questionnaire guideline should be referred to as a test record, and on the other hand subjective suggestion should be avoided in the pre-training process. The interviewee or respondents should be involved in a survey within different times of day to allow for an estimated deviation of indoor thermal environment fluctuation.

Fourthly, assistance software applications are an important method in this research for dealing with large data analysis and parametric analysis of building modeling simulation work. In this study, ‘SPSS’ software package and ‘DesignBuilder’ (DB) state-of-art software tools were used for the field study data set and for different simulation scenarios’ comparative research. Data set management includes the tough task of classifying and exporting or importing data for the PMV calculation with ‘MATLAB’ math-works software, and ‘EXCEL’ of Microsoft Office is also a good tool for doing the transition operation work. DB is an excellent 3-dimensional tool for building inheritance modeling.

7.3 RESEARCH FINDINGS

In this research, all findings seek to answer the main research question mentioned in this PhD thesis Chapter 1, section 1.4: ‘What is the best way to investigate the thermal comfort potential of Chinese low-energy (energy efficient) apartments in HSCW zone?’ This research aims to provide a challenge to the prevailing building thermal environment standards in the Chinese HSCW zone for energy efficient buildings and Chinese healthy housing, technical support for building environment design, an extension of research into psychological adaptation of adaptive thermal comfort in HSCW zone, and an investigation of residential building performance cognition. In response to each sub-quest of the research question there are four main research findings as listed below:

- ***The answer of research sub-question one:***
  The field study results indicated that indoor thermal comfort can not be achieved for the current middle class of low-energy residential buildings located in Yichang of HSCW zone under both seasons of hot summer and cold winter. The overcooling phenomenon is found as a serious discomfort far away from lower limit of current China civil buildings’ thermal environment criteria (China energy efficiency building strategy). It was underestimated in current HSCW zone building design code which usually focus on overheating in hot summer for more challenge of cooling energy consumption.

According to the literature review in the Chapter 2 and the adaptive thermal comfort field study analysis in Chapter 4, indoor comfort faces a great challenge in current low-energy buildings based on current energy efficiency design strategies in HSCW zone of China. Frankly speaking there is not a specific enough set of thermal comfort criteria in today’s Chinese building standards. We can just find few simple temperature controlling ranges in the old version of ‘Design standards for energy efficiency of residential buildings in hot summer and cold winter zone’ (JGJ134-2001), or two single air temperature limits for the indoor thermal environment calculation process (16℃ for winter and 18℃ for summer) (MHURD-PRC 2010). As we know, indoor thermal comfort is a complex and dynamic process, and even if it is theoretically controlled by objective building designs and the use of heating or cooling facilities, it is also affected by occupants’ subjective thermal sensation preferences and regional environment perception experiences. Therefore low-energy (energy efficient) buildings in HSCW zone have been facing a big challenge of the discrepancy between environment limit control in building codes and actual occupancy thermal demand. Actually so-called ‘energy efficiency’ is not a reasonable operation process. By comparing with the UK’s recommended comfort criteria for specific application in residential buildings we can find that the current Chinese building thermal environment code just reaches a low level of the UK operative temperature range and there is no summary of environmental advice, activity level or indoor clothing status description. This research could give a reference point for the further enlargement of residential building environment design standards. According to the monitoring data of the field study, the quantitative analysis indicated that even though the residential buildings’ environments are controlled by split air conditioners (SACs) and other small-power applications in hot summer, they still have 60-70% occupancy hours of overheating, and the maximum indoor air temperature even reached 36.73℃ in case A and 31.06℃ in case B. The mean values are about 28-30℃. For the winter season, overcooling existed in current middle class residential building environments. According to current indoor thermal control in HSCW zone, the limit of 16℃ is for energy efficiency strategic buildings, and the limit of 18℃ is defined as China’s healthy housing technical essential. It is indicated that 65-85% of occupancy hours are below 16℃ and nearly 90% of occupancy hours are lower than 18℃. Overheating and overcooling is a dynamic index based on occupants’ thermal sensations and affected by subjective building environment cognition. It is influenced by occupants’ participation and daily life schedule, and therefore adaptive thermal comfort presents a good way for the study of regional acceptable indoor comfort to defeat the unbearable thermal potential. In the other method of on-site measurement being synchronised with the subjective questionnaire records, it is indicated that the testing duration saw the mean air temperature at about 31-32℃ in case A and 29-30℃ in case B. Therefore the adaptive thermal comfort survey focused on the overheating indoor environment. For the winter season, the records reveal that the mean air temperatures are about 13-14℃ in case A and 10-11℃ in case B. Therefore the adaptive thermal comfort survey focused on the overcooling environment.

- ***The answer of research sub-question two:***

  Adaptive thermal study represented occupants can tolerate a wider indoor air temperature range by subjective perception under both hot and cold situations in residential buildings under specific HSCW zone conditions. Moreover the difference of personal thermal sensitivity could be found in two different selected cases. The field studies displayed that the neutral temperature in Yichang is 21.4°C in case A and 22.6°C in case B. The acceptable thermal sensation preference ranges from 15.4°C to 27.4°C in case A, to 16.8°C to 28.3°C in case B.

In this research, the adaptive thermal comfort model provides an adaptive coefficient, thermal sensitivity guideline, neutral point of indoor air temperature, and thermal comfort range for hot and cold situations related to different residential building layouts. This helps answer the question of what practical thermal comfort is in residential building environments in HSCW zone. In this research the chosen field study is in Yichang city, within a specific part of the HSCW zone (the middle part of HSCW zone with III_C climatic situations) (MHURD-PRC and GAQSIQ-PRC 1993b). Two different prototype cases are chosen to investigate the adaptive coefficient by the AMV method of subjective assessment and the PMV method of objective calculations with on-site thermal parameter measurements. It is a first for extending adaptive thermal comfort research in residential building environments, which are usually controlled by mixed mode combined with natural ventilation and split air conditioner adjustment. There is more Chinese thermal research focused on NV or non-domestic buildings (university classroom, office and retail space). More research is concerned with case studies in the east part of HSCW zone, for example Shanghai (III_A climatic situations) and the west part of the Chongqing area (III_B). This research usually deals with the standard HSCW zone, but the III_c climatic area has its own specific conditions and requires an adaptive approach to indoor thermal comfort. According to the field study of subjective and objective data collections, the AMV model of subjective perception preferences has relatively low levels of explanatory power by linear regression equations linked with air temperatures. The PMV model of objective empirical calculation overestimates the thermal environment assessment in hot summer and underestimates the building environment in cold winter. The environment adaptive coefficient can balance AMV and PMV by using a PMV model to present an actual thermal assessment with high levels of explanation by linear regression equations. It is useful for describing a dynamic thermal comfort temperature altering process that is very important in affecting building environment performance. It could be a good reference point for research assessing residential building environment in specific HSCW zones. In this study discrepancies in different cases' prototypes exist in the thermal comfort assessment results. The thermal sensitivity results in both two cases for hot and cold conditions are presented in Figure 4.9, where it is indicated that the long depth and narrow facade prototype of case A has lower sensitivity in both hot and cold situations regardless of AMV votes and PMV calculations, in comparison with case B's square layout with a wide facade and short depth. For the local occupants, regardless of whether they are in case A or case B, they have higher sensitivity for hot situations than cold situations. The adaptive coefficient presented a PMV model in which case B has a higher index (0.215) under hot situations than that of case A (0.174). For the cold situations case A has an index of -0.192 and case B obtains an index of -0.072. The related research developed by Yao et al. in 2009 calculated the adaptive coefficient 'λ' for warm and cool conditions in classrooms in the Chongqing University (west HSCW zone): 0.293 and -0.125 respectively (R. Yao et al. 2009). The research conducted by Singh et al. in 2011 for different climatic zones in northeast India also presented a different adaptive coefficient for all the differences of occupants' adaptations. These various indices take into account the local climate and socio-cultural setup (Singh et al. 2011).

As the literature review and field study work shows, regional climate and subjective participation also has a significant effect on indoor thermal comfort cognition. In this study the occupants' subjective adaptive preferences of indoor thermal perception in residential building environments vindicates the psychological adaptation awareness of the adaptive approach. That provides a potential for building information modeling (BIM) research. It is an extension study for adaptive thermal comfort for residential building environment. The field study focuses on people's anthropological factors, socio-cultural background, seasonal differences and building layout specifics. The related empirical equations are based on the multiple regressions of a step-wise method. The seasonal equations can present multiple options of acceptable thermal comfort, which combined with the seasonal monthly outdoor air temperatures can obtain the maximum and minimum margin equations correlated with the prevailing regional climate for residential building operation. Moreover the explanations of the determining coefficient are at a high level of above 0.9.

- ***The answer of research sub-question three:***
  Based on building performance idea to improve the conflict of unbalance between building energy saving issues and indoor thermal comfort demand, the adaptive thermal comfort approach of adaptive coefficient and study of subjective psychological preference within special climatic conditions are two efficiency methods to explain human actual thermal comfort demand and acceptable thermal range. They are both good methods of subjective evaluation for indoor thermal environment.

Thermal comfort and energy conservation are two key issues for building environment design, and the building environment cannot be effectively designed by applying only one of them. That is a key point of sustainable building assessment. In the energy consumption field study investigation it was hard to collect valid data, caused by the diversity of indoor facility use. This kind of work is based on simulation program application. According to the adaptive thermal comfort survey, regional thermal comfort control findings are designed as simulation scenarios, compared with the current low standard of actual energy-efficient building designs and the high standard of the prescribed China healthy housing standard. The simulation results represent the energy breakdown of monthly energy use for lighting, heating and cooling. It is indicated that the ‘adaptive’ approach makes a 6-10% greater energy saving than the application of China’s healthy housing environment control; however, it actually needs more energy use for indoor thermal comfort compared with the energy efficiency building standard of building environment control and increasing ratio of energy consumption is about 11-21%. For the detailed results of heating and cooling, building layout makes a difference to the energy performance. China’s current healthy housing standard underestimates the occupants’ adaptive capacity for cold indoor situations while overestimating their capacity for hot indoor situations in these two selected cases and their different prototypes. The energy efficiency standard in HSCW zone totally overestimates occupants’ adaptive capacity for all indoor thermal situations in these two cases. Thinking about the effect different of building layouts, case A has a more significant discrepancy between the adaptive approach of thermal comfort and the high level of the healthy housing standard. However, the discrepancy between the adaptive thermal comfort method and the current low level of energy efficiency standards for residential buildings in HSCW zone in China is greater in case B.

Building performance is a real area for improving the limitations of objective building design and the current one-dimensional algorithm of building environment research. The subjectivity of people-participation adds one more determining algorithm for indoor thermal comfort assessment and total energy consumption. Different ages and genders always have significant differences in all seasons with different thermal preferences. The socio-cultural background factor of education level has a significant impact during spring, summer and winter, but apparently not in autumn.

- ***The answer of research sub-question four:***
  For current China’s building environment design, there is lack of parametric design study of subjective participation and also exists some misunderstanding of relationship between building shape design and energy saving issues. The simulation work with adaptive thermal scenario input is represented clearly superior for indoor thermal comfort to the energy efficiency scenario and more energy saving than health housing scenario in HSCW zone of China. The ‘Building Shape Coefficient’ defined in China current design standard have limited and impeded China residential building development with energy saving demand. Building performance of energy consumption would be better defined by the energy efficiency per unit of indoor floor area.

As a pioneering work, this research provides a series of potential opportunities to improve Chinese residential buildings (low-energy buildings) under HSCW zone climatic conditions. The current residential buildings in today's China are designed as low energy buildings, which is a mandatory limit for the design document approval process. Therefore this investigation could suggest out some subjective and objective potential for building environment design.

The thermal comfort and energy consumption assessments in China's HSCW zone for residential building environment design should consider the actual environment control in mixed-mode, which is significant for the residential building operation in the building's post-construction lifecycle. In this research the questionnaire results expressed that although the SAC control is the dominant facility for building thermal environment control, it is not always the first choice of indoor mechanism adjustment approaches in the living room. Small powered devices are usually first choice for indoor heating and cooling. In the bedroom space SAC is the first choice for heating but not for cooling.

The personal building environment cognition tendency of thermal comfort and energy saving has seasonal differences in China's HSCW zone for residential building occupancy. In this study it is found that a preference for energy efficiency usually happens in the transitional seasons of spring and autumn, and a higher percentage of support for thermal comfort occurs in the extreme seasons of hot summer and cold winter. Those results reveal a dynamic subjective participation tendency and a potential suggestion for a dynamic residential building environment control. In this study nearly 50% of respondents thought the level of energy use is based on living habits in the transitional seasons of spring and autumn, however in extreme seasons the dominant percentage of energy use is dependent upon the local weather conditions. In this study the physiological impact is relevant for determining thermal comfort in all seasons. Psychological impact is found to be more important than behavioural adjustment during hot summer and the opposite result is obtained in cold winter.

7.4 LIMITATIONS AND FUTURE WORK

In this research some real hardship and barriers should be taken into account, some points of which are listed below.

Firstly, this research is focused on China's residential building environments. Residential buildings are very private spaces and occupant participation initiatives are hard to do in independent field study. Therefore the interviewee has limitations for on-site measurement within an adaptive thermal comfort survey. Sometimes the respondent is alone in the testing process and sometimes a few interviewees (2-3) give their answer at the same indoor scenario. The solo record and the group work may have different effectiveness for the PMV model in China's HSCW zone for residential buildings. For the further study, respondents' interactive disturbance should be concerned for the difference of thermal sensation within solo process and group work, it is could be more useful in higher-level official legislation for building environment design.

Secondly, this research is based on two different prototypes of typical middle class Chinese residential buildings, and the limitation of the building layout certainly exists for other kinds of apartments too for example, villa building, China traditional wooden house (residential) and so on. These two middle class prototype cases are common building designs for different commercial targets. Case A is a kind of land-saving building layout design with a narrow facade and long depth. Case B is a square building layout shape with a wide facade and relatively short depth. Case A is an end unit of a building block and it has some opening areas located at the side wall, because this kind of long depth building layout has indoor lighting problems in the middle room. Case B is a very typical building layout, with an internal corridor to separate rooms running towards the front and back opening of the building. More and more building layout designs provide more living options for building environments, and the improvement of indoor space layout of building environments has a strong link with improved interior microclimates. This research started an adaptive thermal comfort field study with these two typical prototypes and more thermal environment assessments could be launched for variant China housing research combined with multidisciplinary study in the future.

Thirdly, in this research simulation work, parametric study is based on the student version of 'DesignBuilder' software and cannot take over 50 zone calculations. Therefore the high-rise building simulation work is hard to detail in every zone, especially because for the whole residential building block there are over 10 zones per level. In this study the simulation work did not take into account kitchens, toilets and some indoor spaces without SAC control, and also did not deeply research on heat transfer from neighboring space; that is an interesting topic for further study of high-rise residential buildings' heat transfer properties.

Fourthly, in this study the subjective assessments of occupant behavior of occupancy, lighting and HVAC usage have regional difference affected by cognition of thermal environment, economic level, living habit and household income. Although it is a limitation in this study, effective for middle-class city in HSCW zone.

As well as the limitations with the basic of further study mentioned above there is a summary of possible future works. The adaptive thermal comfort model has been approved as an effective correction for Fanger’s PMV model. This extension study could be used for residential buildings’ development in today’s China. Various future work is needed to gain more knowledge on particular characteristics of China’s building industry’s development, government residential building strategies, regional technical essentials of building environment design, socio-cultural study and building occupancy information and operation issues.

- *Policy and industry norms*

The legislation of residential building environment standards development needs more detailed technical essentials for indoor adaptive thermal comfort research in special climatic zones. A large amount of database information needs comprehensive field study and questionnaire improvement for regional adaptive coefficient and actual thermal comfort ranges. Better regional empirical frameworks could be constructed for regional residential building environments.

- *Public participation*

How to increase the chances of occupancy participation for building environment design is a further question that should be addressed in the future. Subjective participation is a key point for indoor thermal comfort and energy consumption issues. For residential building research the occupancy response is hard to obtain. In future work, the energy metering system should not only concern the electricity (gas) bill but could also be combined with an indoor thermal comfort assessment.

- *Building environment cognition*

Dynamic adaptive thermal comfort needs testing on more building environment design types. For the conventional residential building design, the spatial function, aesthetic concept and construction material application are usually undefined in the initial building environment design stages. The performance target of building environments should be clear from day one.

- *Parametric design and intelligent buildings*

Parametric building design is based on subjective information collection, in which psychological expectation and preference of environment adaptation are more controllable than occupants’ behaviors in residential building environment. As for the development of intelligent buildings, subjective environment demands could be dynamically described by the use of computerised information processing.

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APPENDIX A–A1: GENERAL INFORMATION COLLECTION

PART 1-BACKGROUND (第一部分背景)			
1.1 Apartment Unit (测试房型)	**Case 1** (房型 1) □ **Case 2** (房型 2) □	**1.2 Seasonal Condition** (测试季节)	**Spring**(春季)□ **Summer** (夏季)□ **Autumn**(秋季)□ **Winter** (冬季)□
1.3 Occupant's Age (年龄)		**1.4 Gender**(性别)	**Male**(男性) □ **Female**(女性) □
1.5 Occupant's Education(教育背景)	**Compulsory Education**(义务教育及其以下) □ **Basic Professional Education** (基础专业教育，职业及本科教育) □ **Graduated Professional Education** (高级专业教育,硕士及以上) □		
1.6 Job Style of Occupant (职业类型)	**Manual**(体力劳动)□ **Mental**(脑力劳动)□ **Mixed** (混合型劳动) □		

1.7 Living History (居住经历)	**Non-urban**(非城市地区)	**Urban**(城市地区)
	(Ys 年)	(Ys 年)

PART 2-APARTMENT THERMAL ENVIRONMENT CONTROL (第二部分户型热环境控制)				
	Living Room (客厅)		**Main Bedroom**(卧室)	
	Heating (制热)	**Cooling** (制冷)	**Heating** (制热)	**Cooling** (制冷)
2.1. Main Device (主要设备) (如果多选则分别填写)	**AC**(空调)□ **EH**(电暖炉)□ **Floor heating**(地暖)□ **HWR** (水暖气片)□	**AC**(空调)□ **EC**(电冷气)□ **Fan** (电风扇)□	**AC**(空调)□ **EH**(电暖炉)□ **Floor heating**(地暖)□ **HWR** (水暖气片)□	**AC**(空调)□ **EC**(电冷气)□ **Fan** (电风扇)□
2.2 EER/COP[1](设备能效比)				
2.3 Set-point T(℃)[2](设定温度)	First day (第一天):	Mean (平均值):	First day (第一天):	Mean (平均值):
	Third day(第三天):		Third day(第三天):	
	Fifth day (第五天):		Fifth day (第五天):	

PART 3-OCCUPANCY ENVIRONMENT PREFERENCE(第三部分用户环境偏好)									
3.5 Attitude of energy savingand indoor thermal comfort (节能与室内热舒适的态度)	-4□ 完全 节能	-3□ 重点 节能	-2□ 侧重 节能	-1□ 相对 节能	0□ 相同	1□ 相对 舒适	2□ 侧重 舒适	3□ 重点 舒适	4□ 完全 舒适
	3.5.1 Energy Use(能耗影响因素):								
	Living habit(居住习惯)□**Household Income**(住户收入)□ **Energy-efficient Device**(节能设备)□**Local weather** (当地气候)□								
	3.5.2 Thermal Comfort Requirement(热舒适需求影响因素)[3]:								
	Physiological(生理因素) □ **Psychological**(心理因素) □ **Behavioural**(行为因素) □								

PART 4-OCCUPANCY ACTIVITY SCHEDULE (第三部分用户环活动比重调研)

3.1 Occupant Activity Schedule (住户行为时间表) (根据间隔时间内使用频率给0-10的使用情况的分数：0表示没有行为发生；10表示在间隔时间内一直持续有相关行为发生；中间各数值从小到大分别表示发生频率由小到大)	**Internal Zones** (内部区域)	**Living Room** (客厅)			**Main Bedroom**(主卧室)		
	Intervals(间隔时间)	**E**(设备)	**L**(照明)	**H**(人)	**E**(设备)	**L**(照明)	**H**(人)
	00:00-01:00(0-10)						
	01:00-02:00 (0-10)						
	02:00-03:00 (0-10)						
	03:00-04:00 (0-10)						
	04:00-05:00 (0-10)						
	05:00-06:00 (0-10)						
	06:00-07:00 (0-10)						
	07:00-08:00 (0-10)						
	08:00-09:00 (0-10)						
	09:00-10:00 (0-10)						
	10:00-11:00 (0-10)						
	11:00-12:00 (0-10)						
	12:00-13:00 (0-10)						
	13:00-14:00 (0-10)						
	14:00-15:00 (0-10)						
	15:00-16:00 (0-10)						
	16:00-17:00 (0-10)						
	17:00-18:00 (0-10)						
	18:00-19:00 (0-10)						
	19:00-20:00 (0-10)						
	20:00-21:00 (0-10)						
	21:00-22:00 (0-10)						
	22:00-23:00 (0-10)						
	23:00-24:00 (0-10)						
	Intervals(间隔时间)	**E**(设备)	**L**(照明)	**H**(人)	**E**(设备)	**L**(照明)	**H**(人)

NOTES AND EXPLANATION(解释说明)

1. Energy Efficiency Ratio(EER/COP) could be checked by interviewee with the equipment guideline label, which the value is marked in the China Energy Label (CEL). (能效比可以让受访者在设备的说明标牌上查找，具体参数标注在设备上的中国能效标识（CEL）的标志上)
2. Set-point Temperature means the air-conditioner cooling/heating recommended temperature. In general suggestion 26℃ is set in summer and 18℃ in winter. However interviewee does not need to be interrupted by the recommended criteria and sampling value is up to the occupants' personal choice. (设定温度是空调制冷/加热时的推荐温度。例如，通常在夏季设定为26℃，而在冬天设定为18℃)
3. In this part, three impact factors are designed to describe the indoor thermal comfort. Physiological factors include metabolism level difference of human body and the rate difference of perspiration. The psychological factors stand for the diversity of thermal sensation made by social and cultural background. The behavioural factors think about the occupants' real activities occurred in the real scenario. (在有关热舒适需求影响因素这部分设置了三类影响因素。生理因素包括了人体新陈代谢水平的差异性以及出汗率的不同。心理因素代表了由于社会文化背景的不同所造成的热感知不同的一切因素。行为因素是考虑了居住者在真实场景中所有真实行为的因素)

APPENDIX A–A2: thermal sensation survey

EXPLANATION GUIDELINE (解释说明)

1.1 Thermal experience (热体验评价) （**PMV**）	**Cold** (寒冷)	**Cool** (凉快)	**Slightly cool** (微凉)	**Neutral** (热中和)	**Slightly warm** (微暖)	**Warm** (温暖)	**Hot** (热)
	-3	-2	-1	0	1	2	3

1.2 Overall comfort (总体舒适感评价)	**Comfortable** (舒适)	**Slightly uncomfortable** (轻微不舒适)	**Uncomfortable** (不舒适)	**Very uncomfortable** (非常不舒适)	**Extremely uncomfortable** (极端不舒适)
	0	1	2	3	4
1.3 Thermal tolerance (热容忍评价)	**Perfectly tolerable** (完全能够容忍)	**Slightly diffcult to tolerate** (轻微难以忍受)	**Fairly difficult to tolerate** (完全难以忍受)	**Very difficult to tolerate** (非常难以忍受)	**Intolerable** (无法忍受)
	0	1	2	3	4

1.4 Daily wear clothing (日常衣着)	**Clo**	**1.5 Activity** (行为活动)	**Metabolic rate**
Panties, T-shirt, shorts, light socks, sandals (短衬裤，T 恤，短裤，浅色短袜，凉鞋)	0.3	**Sleeping** (睡觉)	0.7
Underpants, shirt with short sleeves, light trousers, light socks, shoes (内衬裤，短袖衬衣，浅色裤子，浅色短袜，鞋)	0.5	**Reclining** (躺卧休息)	0.8
		Seated, Quiet (安静地坐着)	1.0
Panties, petticoat, stockings, dress, shoes (短衬裤，衬裙，长袜，连衣裙，鞋)	0.7	**Standing, Relaxed** (放松的站立)	1.2
Underwear, shirt, trousers, socks, shoes (内衣，衬衫，长裤，短袜，鞋)	0.7	**Cooking** (烹饪)	1.6-2.0
Panties, shirt, trousers, jacket, stocks, shoes (短衬裤，衬衫，长裤，夹克，短袜，鞋)	1.00	**Housing cleaning** (房屋清洁)	2.0-3.4
Panties, stocking, blouse, long shirt, jacket, shoes (短衬裤，长袜，女衬衣，长衬衣，夹克，鞋)	1.10	**Seated, Heavy limb movement** (坐着有大幅度动作)	2.2
Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes (长款内衣，衬衫，长裤，V 领毛衫，夹克，短袜，鞋)	1.30	**Walking-0.9 m/s**(行走)	2.0
		Walking-1.2 m/s (行走)	2.6
Underwear with short sleeves and legs, shirt, trousers, Vest, jacket, coat, socks, shoes (短款内衣，衬衫，长裤，背心，夹克，外套，短袜，鞋)	1.50	**Walking-1.8 m/s** (行走)	3.8

Day ()	**PART 1-THERMAL SURVEY in LIVING／BED ROOM** (热舒适调研)							
Test 1	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)								
Second Half (第二个半小时)								
Test 2	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)								
Second Half (第二个半小时)								
Test 3	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)								
Second Half (第二个半小时)								

THE END

(问卷结束)

THANKS YOUR PARTICIPATION AND PATIENCE

(感谢您的耐心参与)

SAMPLE EXAMPLE 1:

APPENDIX A–(SAMPLES) A1: GENERAL INFORMATION COLLECTION

PART 1-BACKGROUND (第一部分背景)			
1.1 Apartment Unit (测试房型)	**Case 1** (房型 1) ☑ **Case 2** (房型 2) □	**1.2 Seasonal Condition** (测试季节)	**Spring**(春季)□ **Summer** (夏季)☑ **Autumn**(秋季)□ **Winter** (冬季)□
1.3 Occupant's Age (年龄)	29	**1.4 Gender**(性别)	**Male**(男性) ☑ **Female**(女性) □
1.5 Occupant's Education(教育背景)	**Compulsory Education**(义务教育及其以下) □ **Basic Professional Education** (基础专业教育，职业及本科教育) □ **Graduated Professional Education** (高级专业教育,硕士及以上) □		
1.6 Job Style of Occupant (职业类型)	**Manual**(体力劳动)□ **Mental**(脑力劳动)☑ **Mixed** (混合型劳动) □		
1.7 Living History (居住经历)	**Non-urban**(非城市地区)	**Urban**(城市地区)	
	0 (Ys 年)	29 (Ys 年)	

PART 2-APARTMENT THERMAL ENVIRONMENT CONTROL (第二部分户型热环境控制)				
	Living Room (客厅)		**Main Bedroom**(卧室)	
	Heating (制热)	**Cooling** (制冷)	**Heating** (制热)	**Cooling** (制冷)
2.1. Main Device (主要设备) (如果多选则分别填写)	**AC**(空调)☑ 2 **EH**(电暖炉)☑ 1 **Floor heating**(地暖)□ **HWR** (水暖气片)□	**AC**(空调)☑ 1 **EC**(电冷气)□ **Fan** (电风扇)□	**AC**(空调)☑ 1 **EH**(电暖炉)□ **Floor heating**(地暖)□ **HWR** (水暖气片)□	**AC**(空调)☑ 1 **EC**(电冷气)□ **Fan** (电风扇)☑ 2
2.2 EER/COP[1](设备能效比)	2.79	2.79	3.39	3.39
2.3 Set-point T(℃)[2](设定温度)	First day (第一天): 24	Mean (平均值): 23	First day (第一天):24	Mean (平均值): 24
	Third day(第三天):24		Third day(第三天):24	
	Fifth day (第五天): 21		Fifth day (第五天):24	

PART 3-OCCUPANCY ENVIRONMENT PREFERENCE(第三部分用户环境偏好)									
3.5 Attitude of energy savingand indoor thermal comfort (节能与室内热舒适的态度)	-4□ 完全 节能	-3□ 重点 节能	-2□ 侧重 节能	-1□ 相对 节能	0□ 相同	1□ 相对 舒适	2☑ 侧重 舒适	3□ 重点 舒适	4□ 完全 舒适
	3.5.1 Energy Use(能耗影响因素):								
	Living habit(居住习惯)□**Household Income**(住户收入)□ **Energy-efficient Device**(节能设备)□**Local weather** (当地气候)☑								
	3.5.2 Thermal Comfort Requirement(热舒适需求影响因素)[3]:								
	Physiological(生理因素) □ **Psychological**(心理因素)☑ **Behavioural**(行为因素) □								

PART 4-OCCUPANCY ACTIVITY SCHEDULE (第三部分用户环活动比重调研)

	Internal Zones (内部区域)	**Living Room** (客厅)			**Main Bedroom**(主卧室)		
	Intervals(间隔时间)	**E**(设备)	**L**(照明)	**H**(人)	**E**(设备)	**L**(照明)	**H**(人)
3.1 Occupant Activity Schedule (住户行为时间表) (根据间隔时间内使用频率给 0-10 的使用情况的分数：0 表示没有行为发生；10 表示在间隔时间内一直持续有相关行为发生；中间各数值从小到大分别表示发生频率由小到大)	00:00-01:00(0-10)	0	4	0	5	3	10
	01:00-02:00 (0-10)	0	4	0	0	0	10
	02:00-03:00 (0-10)	0	0	0	0	0	10
	03:00-04:00 (0-10)	0	0	0	0	0	10
	04:00-05:00 (0-10)	0	0	0	0	0	10
	05:00-06:00 (0-10)	0	0	0	0	0	10
	06:00-07:00 (0-10)	0	0	0	0	0	10
	07:00-08:00 (0-10)	0	0	0	0	0	8
	08:00-09:00 (0-10)	5	0	5	8	5	5
	09:00-10:00 (0-10)	0	0	0	0	0	0
	10:00-11:00 (0-10)	0	0	0	0	0	0
	11:00-12:00 (0-10)	0	0	0	0	0	0
	12:00-13:00 (0-10)	0	0	0	0	0	0
	13:00-14:00 (0-10)	0	0	0	0	0	10
	14:00-15:00 (0-10)	0	0	0	0	0	0
	15:00-16:00 (0-10)	0	0	0	0	0	0
	16:00-17:00 (0-10)	0	0	0	0	0	0
	17:00-18:00 (0-10)	3	0	8	3	0	0
	18:00-19:00 (0-10)	5	5	8	4	3	0
	19:00-20:00 (0-10)	10	10	10	0	4	0
	20:00-21:00 (0-10)	10	10	10	0	5	0
	21:00-22:00 (0-10)	5	3	0	0	5	0
	22:00-23:00 (0-10)	5	0	0	5	5	8
	23:00-24:00 (0-10)	5	0	0	5	3	10
	Intervals(间隔时间)	**E**(设备)	**L**(照明)	**H**(人)	**E**(设备)	**L**(照明)	**H**(人)

NOTES AND EXPLANATION(解释说明)

1. Energy Efficiency Ratio(EER/COP) could be checked by interviewee with the equipment guideline label, which the value is marked in the China Energy Label (CEL). (能效比可以让受访者在设备的说明标牌上查找，具体参数标注在设备上的中国能效标识（CEL）的标志上)
2. Set-point Temperature means the air-conditioner cooling/heating recommended temperature. In general suggestion 26℃ is set in summer and 18℃ in winter. However interviewee does not need to be interrupted by the recommended criteria and sampling value is up to the occupants' personal choice. (设定温度是空调制冷/加热时的推荐温度。例如，通常在夏季设定为 26℃，而在冬天设定为 18℃)
3. In this part, three impact factors are designed to describe the indoor thermal comfort. Physiological factors include metabolism level difference of human body and the rate difference of perspiration. The psychological factors stand for the diversity of thermal sensation made by social and cultural background. The behavioural factors think about the occupants' real activities occurred in the real scenario. (在有关热舒适需求影响因素这部分设置了三类影响因素。生理因素包括了人体新陈代谢水平的差异性以及出汗率的不同。心理因素代表了由于社会文化背景的不同所造成的热感知不同的一切因素。行为因素是考虑了居住者在真实场景中所有真实行为的因素)

APPENDIX A–(SAMPLES)A2: thermal sensation survey

EXPLANATION GUIDELINE (解释说明)

1.1 Thermal experience (热体验评价) （**PMV**）	**Cold** (寒冷)	**Cool** (凉快)	**Slightly cool** (微凉)	**Neutral** (热中和)	**Slightly warm** (微暖)	**Warm** (温暖)	**Hot** (热)
	-3	-2	-1	0	1	2	3

1.2 Overall comfort (总体舒适感评价)	**Comfortable** (舒适)	**Slightly uncomfortable** (轻微不舒适)	**Uncomfortable** (不舒适)	**Very uncomfortable** (非常不舒适)	**Extremely uncomfortable** (极端不舒适)
	0	1	2	3	4

1.3 Thermal tolerance (热容忍评价)	**Perfectly tolerable** (完全能够容忍)	**Slightly diffcult to tolerate** (轻微难以忍受)	**Fairly difficult to tolerate** (完全难以忍受)	**Very difficult to tolerate** (非常难以忍受)	**Intolerable** (无法忍受)
	0	1	2	3	4

1.4 Daily wear clothing (日常衣着)	**Clo**	**1.5 Activity** (行为活动)	**Metabolic rate**
Panties, T-shirt, shorts, light socks, sandals (短衬裤，T 恤，短裤，浅色短袜，凉鞋)	0.3	**Sleeping** (睡觉)	0.7
Underpants, shirt with short sleeves, light trousers, light socks, shoes (内衬裤，短袖衬衣，浅色裤子，浅色短袜，鞋)	0.5	**Reclining** (躺卧休息)	0.8
		Seated, Quiet (安静地坐着)	1.0
Panties, petticoat, stockings, dress, shoes (短衬裤，衬裙，长袜，连衣裙，鞋)	0.7	**Standing, Relaxed** (放松的站立)	1.2
Underwear, shirt, trousers, socks, shoes (内衣，衬衫，长裤，短袜，鞋)	0.7	**Cooking** (烹饪)	1.6-2.0
Panties, shirt, trousers, jacket, stocks, shoes (短衬裤，衬衫，长裤，夹克，短袜，鞋)	1.00	**Housing cleaning** (房屋清洁)	2.0-3.4
Panties, stocking, blouse, long shirt, jacket, shoes (短衬裤，长袜，女衬衣，长衬衣，夹克，鞋)	1.10	**Seated, Heavy limb movement** (坐着有大幅度动作)	2.2
Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes (长款内衣，衬衫，长裤，V 领毛衫，夹克，短袜，鞋)	1.30	**Walking-0.9 m/s**(行走)	2.0
		Walking-1.2 m/s (行走)	2.6
Underwear with short sleeves and legs, shirt, trousers, Vest, jacket, coat, socks, shoes (短款内衣，衬衫，长裤，背心，夹克，外套，短袜，鞋)	1.50	**Walking-1.8 m/s** (行走)	3.8

Day ()	PART 1-THERMAL SURVEY in LIVING / [✓ BED ROOM] (热舒适调研)							
Test 1	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)	3	2	1	0.5	1	29.2 30.4	75.8%	0.1
Second Half (第二个半小时)	3	1	1	0.5	0.8	29.5 31.1	71.7%	0.3
Test 2	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)	3	2	1	0.5	1	29.6 30.5	80.2%	0.2
Second Half (第二个半小时)	3	2	2	0.5	1.2	29.5 30.4	78.8%	0.1
Test 3	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)								
Second Half (第二个半小时)								

THE END

(问卷结束)

THANKS YOUR PARTICIPATION AND PATIENCE

(感谢您的耐心参与)

SAMPLE EXAMPLE 2:

APPENDIX A–(SAMPLES) A1: GENERAL INFORMATION COLLECTION

PART 1-BACKGROUND (第一部分背景)

1.1 Apartment Unit (测试房型)	**Case 1** (房型 1) □ **Case 2** (房型 2) ☑	**1.2 Seasonal Condition** (测试季节)	**Spring**(春季)□ **Summer** (夏季)☑ **Autumn**(秋季)□ **Winter** (冬季)□
1.3 Occupant's Age (年龄)	58	**1.4 Gender**(性别)	**Male**(男性) □ **Female**(女性) ☑
1.5 Occupant's Education(教育背景)	**Compulsory Education**(义务教育及其以下) □ **Basic Professional Education** (基础专业教育，职业及本科教育) □ **Graduated Professional Education** (高级专业教育,硕士及以上) □		
1.6 Job Style of Occupant (职业类型)	**Manual**(体力劳动)□ **Mental**(脑力劳动)□ **Mixed** (混合型劳动) ☑		
1.7 Living History (居住经历)	**Non-urban**(非城市地区) 20 (Ys 年)		**Urban**(城市地区) 38 (Ys 年)

PART 2-APARTMENT THERMAL ENVIRONMENT CONTROL (第二部分户型热环境控制)

	Living Room (客厅)		**Main Bedroom**(卧室)	
	Heating (制热)	**Cooling** (制冷)	**Heating** (制热)	**Cooling** (制冷)
2.1. Main Device (主要设备) (如果多选则分别填写)	**AC**(空调)☑ 2 **EH**(电暖炉)☑ 1 **Floor heating**(地暖)□ **HWR** (水暖气片)□	**AC**(空调)☑ 1 **EC**(电冷气)□ **Fan** (电风扇)☑ 2	**AC**(空调)☑ **EH**(电暖炉)□ **Floor heating**(地暖)□ **HWR** (水暖气片)□	**AC**(空调)☑ 1 **EC**(电冷气)□ **Fan** (电风扇)☑ 2
2.2 EER/COP[1](设备能效比)				
2.3 Set-point T(℃)[2](设定温度)	First day (第一天): 23 Third day(第三天): 23 Fifth day (第五天): 23	Mean (平均值): 23	First day (第一天): 26 Third day(第三天): 26 Fifth day (第五天): 26	Mean (平均值): 26

PART 3-OCCUPANCY ENVIRONMENT PREFERENCE(第三部分用户环境偏好)

3.5 Attitude of energy savingand indoor thermal comfort (节能与室内热舒适的态度)	-4□ 完全 节能	-3□ 重点 节能	-2□ 侧重 节能	-1□ 相对 节能	0□ 相同	1☑ 相对 舒适	2□ 侧重 舒适	3□ 重点 舒适	4□ 完全 舒适
	3.5.1 Energy Use(能耗影响因素):								
	Living habit(居住习惯)□**Household Income**(住户收入)□ **Energy-efficient Device**(节能设备)□**Local weather** (当地气候)☑								
	3.5.2 Thermal Comfort Requirement(热舒适需求影响因素)[3]:								
	Physiological(生理因素) ☑ **Psychological**(心理因素) □ **Behavioural**(行为因素) □								

PART 4-OCCUPANCY ACTIVITY SCHEDULE (第三部分用户环活动比重调研)

	Internal Zones (内部区域)	Living Room (客厅)			Main Bedroom(主卧室)		
	Intervals(间隔时间)	E(设备)	L(照明)	H(人)	E(设备)	L(照明)	H(人)
3.1 Occupant Activity Schedule (住户行为时间表) (根据间隔时间内使用频率给 0-10 的使用情况的分数：0 表示没有行为发生；10 表示在间隔时间内一直持续有相关行为发生；中间各数值从小到大分别表示发生频率由小到大)	00:00-01:00(0-10)	0	0	0	10	0	10
	01:00-02:00 (0-10)	0	0	0	10	0	10
	02:00-03:00 (0-10)	0	0	0	10	0	10
	03:00-04:00 (0-10)	0	0	0	10	0	10
	04:00-05:00 (0-10)	0	0	0	10	0	10
	05:00-06:00 (0-10)	0	0	0	5	0	10
	06:00-07:00 (0-10)	5	3	10	0	0	0
	07:00-08:00 (0-10)	8	0	10	0	0	0
	08:00-09:00 (0-10)	8	0	10	0	0	0
	09:00-10:00 (0-10)	0	0	0	0	0	0
	10:00-11:00 (0-10)	0	0	0	0	0	0
	11:00-12:00 (0-10)	6	0	10	0	0	0
	12:00-13:00 (0-10)	10	0	10	0	0	5
	13:00-14:00 (0-10)	0	0	0	0	0	10
	14:00-15:00 (0-10)	0	0	0	0	0	0
	15:00-16:00 (0-10)	0	0	0	0	0	0
	16:00-17:00 (0-10)	10	0	10	0	0	0
	17:00-18:00 (0-10)	10	4	10	0	0	0
	18:00-19:00 (0-10)	10	6	10	0	0	0
	19:00-20:00 (0-10)	10	10	10	0	0	0
	20:00-21:00 (0-10)	10	10	10	0	0	0
	21:00-22:00 (0-10)	10	10	10	0	0	0
	22:00-23:00 (0-10)	0	0	0	10	10	10
	23:00-24:00 (0-10)	0	0	0	10	5	10
	Intervals(间隔时间)	E(设备)	L(照明)	H(人)	E(设备)	L(照明)	H(人)

NOTES AND EXPLANATION(解释说明)

1. Energy Efficiency Ratio(EER/COP) could be checked by interviewee with the equipment guideline label, which the value is marked in the China Energy Label (CEL). (能效比可以让受访者在设备的说明标牌上查找，具体参数标注在设备上的中国能效标识（CEL）的标志上)
2. Set-point Temperature means the air-conditioner cooling/heating recommended temperature. In general suggestion 26℃ is set in summer and 18℃ in winter. However interviewee does not need to be interrupted by the recommended criteria and sampling value is up to the occupants' personal choice. (设定温度是空调制冷/加热时的推荐温度。例如，通常在夏季设定为 26℃，而在冬天设定为 18℃)
3. In this part, three impact factors are designed to describe the indoor thermal comfort. Physiological factors include metabolism level difference of human body and the rate difference of perspiration. The psychological factors stand for the diversity of thermal sensation made by social and cultural background. The behavioural factors think about the occupants' real activities occurred in the real scenario. (在有关热舒适需求影响因素这部分设置了三类影响因素。生理因素包括了人体新陈代谢水平的差异性以及出汗率的不同。心理因素代表了由于社会文化背景的不同所造成的热感知不同的一切因素。行为因素是考虑了居住者在真实场景中所有真实行为的因素)

APPENDIX A–(SAMPLES)A2: thermal sensation survey

EXPLANATION GUIDELINE (解释说明)

1.1 Thermal experience (热体验评价) （PMV）	Cold (寒冷)	Cool (凉快)	Slightly cool (微凉)	Neutral (热中和)	Slightly warm (微暖)	Warm (温暖)	Hot (热)
	-3	-2	-1	0	1	2	3

1.2 Overall comfort (总体舒适感评价)	Comfortable (舒适)	Slightly uncomfortable (轻微不舒适)	Uncomfortable (不舒适)	Very uncomfortable (非常不舒适)	Extremely uncomfortable (极端不舒适)
	0	1	2	3	4

1.3 Thermal tolerance (热容忍评价)	Perfectly tolerable (完全能够容忍)	Slightly diffcult to tolerate (轻微难以忍受)	Fairly difficult to tolerate (完全难以忍受)	Very difficult to tolerate (非常难以忍受)	Intolerable (无法忍受)
	0	1	2	3	4

1.4 Daily wear clothing (日常衣着)	Clo	1.5 Activity (行为活动)	Metabolic rate
Panties, T-shirt, shorts, light socks, sandals (短衬裤，T恤，短裤，浅色短袜，凉鞋)	0.3	Sleeping (睡觉)	0.7
Underpants, shirt with short sleeves, light trousers, light socks, shoes (内衬裤，短袖衬衣，浅色裤子，浅色短袜，鞋)	0.5	Reclining (躺卧休息)	0.8
		Seated, Quiet (安静地坐着)	1.0
Panties, petticoat, stockings, dress, shoes (短衬裤，衬裙，长袜，连衣裙，鞋)	0.7	Standing, Relaxed (放松的站立)	1.2
Underwear, shirt, trousers, socks, shoes (内衣，衬衫，长裤，短袜，鞋)	0.7	Cooking (烹饪)	1.6-2.0
Panties, shirt, trousers, jacket, stocks, shoes (短衬裤，衬衫，长裤，夹克，短袜，鞋)	1.00	Housing cleaning (房屋清洁)	2.0-3.4
Panties, stocking, blouse, long shirt, jacket, shoes (短衬裤，长袜，女衬衣，长衬衣，夹克，鞋)	1.10	Seated, Heavy limb movement (坐着有大幅度动作)	2.2
Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes (长款内衣，衬衫，长裤，V领毛衫，夹克，短袜，鞋)	1.30	Walking-0.9 m/s(行走)	2.0
		Walking-1.2 m/s (行走)	2.6
Underwear with short sleeves and legs, shirt, trousers, Vest, jacket, coat, socks, shoes (短款内衣，衬衫，长裤，背心，夹克，外套，短袜，鞋)	1.50	Walking-1.8 m/s (行走)	3.8

Day ()	PART 1-THERMAL SURVEY in [✓ LIVING] / BED ROOM (热舒适调研)							
Test 1	Thermal experience (热体验评价)	Overall comfort (总体舒适感评价)	Thermal tolerance (热容忍评价)	Cloth (衣着状况)	Activity (活动状态)	Air temperature (空气温度)	Relative humidity (湿度)	Air velocity (风速)
First Half (第一个半小时)	1	0	0	0.5	1	30 31.1	67.1%	0
Second Half (第二个半小时)	2	1	1	0.3	1	30 31.1	70.6%	0
Test 2	Thermal experience (热体验评价)	Overall comfort (总体舒适感评价)	Thermal tolerance (热容忍评价)	Cloth (衣着状况)	Activity (活动状态)	Air temperature (空气温度)	Relative humidity (湿度)	Air velocity (风速)
First Half (第一个半小时)	1	0	0	0.5	1	30.9 31.5	67.8%	0.1
Second Half (第二个半小时)	1	1	0	0.5	1	30.5 31.4	67%	0.1
Test 3	Thermal experience (热体验评价)	Overall comfort (总体舒适感评价)	Thermal tolerance (热容忍评价)	Cloth (衣着状况)	Activity (活动状态)	Air temperature (空气温度)	Relative humidity (湿度)	Air velocity (风速)
First Half (第一个半小时)	1	1	1	0.5	1	27.6 28.7	78.6%	0
Second Half (第二个半小时)	1	1	1	0.3	1	30.3 31.2	70.2%	0

THE END

(问卷结束)

THANKS YOUR PARTICIPATION AND PATIENCE

(感谢您的耐心参与)

SAMPLE EXAMPLE 3:

APPENDIX A–(SAMPLES) A1: GENERAL INFORMATION COLLECTION

PART 1-BACKGROUND (第一部分背景)

1.1 Apartment Unit (测试房型)	**Case 1** (房型 1)☑ **Case 2** (房型 2) □	**1.2 Seasonal Condition** (测试季节)	**Spring**(春季)□ **Summer** (夏季)□ **Autumn**(秋季)□ **Winter** (冬季)☑
1.3 Occupant's Age (年龄)	30	**1.4 Gender**(性别)	**Male**(男性)☑ **Female**(女性) □
1.5 Occupant's Education(教育背景)	**Compulsory Education**(义务教育及其以下) □ **Basic Professional Education** (基础专业教育，职业及本科教育)☑ **Graduated Professional Education** (高级专业教育,硕士及以上) □		
1.6 Job Style of Occupant (职业类型)	**Manual**(体力劳动)□ **Mental**(脑力劳动)☑ **Mixed** (混合型劳动) □		

1.7 Living History (居住经历)	**Non-urban**(非城市地区)	**Urban**(城市地区)
	0 (Ys 年)	30 (Ys 年)

PART 2-APARTMENT THERMAL ENVIRONMENT CONTROL (第二部分户型热环境控制)

	Living Room (客厅)		**Main Bedroom**(卧室)	
	Heating (制热)	**Cooling** (制冷)	**Heating** (制热)	**Cooling** (制冷)
2.1. Main Device (主要设备) (如果多选则分别填写)	**AC**(空调)☑ 1 **EH**(电暖炉)☑ 3 **Floor heating**(地暖)□ **HWR** (水暖气片)☑ 2	**AC**(空调)☑ 1 **EC**(电冷气)□ **Fan** (电风扇)☑ 2	**AC**(空调)☑ 2 **EH**(电暖炉)□ **Floor heating**(地暖)□ **HWR** (水暖气片)☑ 1	**AC**(空调)☑ 1 **EC**(电冷气)□ **Fan** (电风扇)☑ 2
2.2 EER/COP[1](设备能效比)				
2.3 Set-point T(℃)[2](设定温度)	First day (第一天): 16 Third day(第三天): 16 Fifth day (第五天): 14	Mean (平均值): 15	First day (第一天): 16 Third day(第三天): 18 Fifth day (第五天): 20	Mean (平均值): 18

PART 3-OCCUPANCY ENVIRONMENT PREFERENCE(第三部分用户环境偏好)

3.5 Attitude of energy savingand indoor thermal comfort (节能与室内热舒适的态度)	-4□ 完全 节能	-3□ 重点 节能	-2□ 侧重 节能	-1□ 相对 节能	0□ 相同	1□ 相对 舒适	2☑ 侧重 舒适	3□ 重点 舒适	4□ 完全 舒适
	3.5.1 Energy Use(能耗影响因素):								
	Living habit(居住习惯)□**Household Income**(住户收入)□ **Energy-efficient Device**(节能设备)□**Local weather** (当地气候)☑								
	3.5.2 Thermal Comfort Requirement(热舒适需求影响因素)[3]:								
	Physiological(生理因素)☑ **Psychological**(心理因素) □ **Behavioural**(行为因素)☑								

PART 4-OCCUPANCY ACTIVITY SCHEDULE (第三部分用户环活动比重调研)

3.1 Occupant Activity Schedule (住户行为时间表) (根据间隔时间内使用频率给 0-10 的使用情况的分数：0 表示没有行为发生；10 表示在间隔时间内一直持续有相关行为发生；中间各数值从小到大分别表示发生频率由小到大)	**Internal Zones** (内部区域)	**Living Room** (客厅)			**Main Bedroom**(主卧室)		
	Intervals(间隔时间)	**E**(设备)	**L**(照明)	**H**(人)	**E**(设备)	**L**(照明)	**H**(人)
	00:00-01:00(0-10)	2	3	3	3	5	5
	01:00-02:00 (0-10)	0	0	0	2	0	10
	02:00-03:00 (0-10)	0	0	0	2	0	10
	03:00-04:00 (0-10)	0	0	0	2	0	10
	04:00-05:00 (0-10)	0	0	0	2	0	10
	05:00-06:00 (0-10)	0	0	0	2	0	10
	06:00-07:00 (0-10)	0	2	0	2	5	8
	07:00-08:00 (0-10)	2	8	2	2	5	8
	08:00-09:00 (0-10)	5	5	8	2	0	0
	09:00-10:00 (0-10)	3	0	0	0	0	0
	10:00-11:00 (0-10)	3	0	0	0	0	0
	11:00-12:00 (0-10)	3	0	0	0	0	0
	12:00-13:00 (0-10)	9	0	0	5	0	5
	13:00-14:00 (0-10)	5	0	0	2	0	2
	14:00-15:00 (0-10)	3	0	0	2	0	0
	15:00-16:00 (0-10)	2	0	0	2	0	0
	16:00-17:00 (0-10)	2	0	0	2	0	0
	17:00-18:00 (0-10)	2	0	7	4	0	0
	18:00-19:00 (0-10)	4	5	8	4	0	0
	19:00-20:00 (0-10)	8	10	10	4	0	0
	20:00-21:00 (0-10)	7	10	10	5	0	0
	21:00-22:00 (0-10)	9	10	10	5	5	1
	22:00-23:00 (0-10)	9	10	10	5	6	2
	23:00-24:00 (0-10)	8	10	10	3	8	4
	Intervals(间隔时间)	**E**(设备)	**L**(照明)	**H**(人)	**E**(设备)	**L**(照明)	**H**(人)

NOTES AND EXPLANATION(解释说明)

1. Energy Efficiency Ratio(EER/COP) could be checked by interviewee with the equipment guideline label, which the value is marked in the China Energy Label (CEL). (能效比可以让受访者在设备的说明标牌上查找，具体参数标注在设备上的中国能效标识（CEL）的标志上)
2. Set-point Temperature means the air-conditioner cooling/heating recommended temperature. In general suggestion 26℃ is set in summer and 18℃ in winter. However interviewee does not need to be interrupted by the recommended criteria and sampling value is up to the occupants' personal choice. (设定温度是空调制冷/加热时的推荐温度。例如，通常在夏季设定为 26℃，而在冬天设定为 18℃)
3. In this part, three impact factors are designed to describe the indoor thermal comfort. Physiological factors include metabolism level difference of human body and the rate difference of perspiration. The psychological factors stand for the diversity of thermal sensation made by social and cultural background. The behavioural factors think about the occupants' real activities occurred in the real scenario. (在有关热舒适需求影响因素这部分设置了三类影响因素。生理因素包括了人体新陈代谢水平的差异性以及出汗率的不同。心理因素代表了由于社会文化背景的不同所造成的热感知不同的一切因素。行为因素是考虑了居住者在真实场景中所有真实行为的因素)

APPENDIX A–(SAMPLES)A2: thermal sensation survey

EXPLANATION GUIDELINE (解释说明)

1.1 Thermal experience (热体验评价)（**PMV**）	**Cold** (寒冷)	**Cool** (凉快)	**Slightly cool** (微凉)	**Neutral** (热中和)	**Slightly warm** (微暖)	**Warm** (温暖)	**Hot** (热)
	-3	-2	-1	0	1	2	3

1.2 Overall comfort (总体舒适感评价)	**Comfortable** (舒适)	**Slightly uncomfortable** (轻微不舒适)	**Uncomfortable** (不舒适)	**Very uncomfortable** (非常不舒适)	**Extremely uncomfortable** (极端不舒适)
	0	1	2	3	4
1.3 Thermal tolerance (热容忍评价)	**Perfectly tolerable** (完全能够容忍)	**Slightly diffcult to tolerate** (轻微难以忍受)	**Fairly difficult to tolerate** (完全难以忍受)	**Very difficult to tolerate** (非常难以忍受)	**Intolerable** (无法忍受)
	0	1	2	3	4

1.4 Daily wear clothing (日常衣着)	**Clo**	**1.5 Activity** (行为活动)	**Metabolic rate**
Panties, T-shirt, shorts, light socks, sandals (短衬裤，T 恤，短裤，浅色短袜，凉鞋)	0.3	**Sleeping** (睡觉)	0.7
Underpants, shirt with short sleeves, light trousers, light socks, shoes (内衬裤，短袖衬衣，浅色裤子，浅色短袜，鞋)	0.5	**Reclining** (躺卧休息)	0.8
		Seated, Quiet (安静地坐着)	1.0
Panties, petticoat, stockings, dress, shoes (短衬裤，衬裙，长袜，连衣裙，鞋)	0.7	**Standing, Relaxed** (放松的站立)	1.2
Underwear, shirt, trousers, socks, shoes (内衣，衬衫，长裤，短袜，鞋)	0.7	**Cooking** (烹饪)	1.6-2.0
Panties, shirt, trousers, jacket, stocks, shoes (短衬裤，衬衫，长裤，夹克，短袜，鞋)	1.00	**Housing cleaning** (房屋清洁)	2.0-3.4
Panties, stocking, blouse, long shirt, jacket, shoes (短衬裤，长袜，女衬衣，长衬衣，夹克，鞋)	1.10	**Seated, Heavy limb movement** (坐着有大幅度动作)	2.2
Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes (长款内衣，衬衫，长裤，V 领毛衫，夹克，短袜，鞋)	1.30	**Walking-0.9 m/s**(行走)	2.0
		Walking-1.2 m/s (行走)	2.6
Underwear with short sleeves and legs, shirt, trousers, Vest, jacket, coat, socks, shoes (短款内衣，衬衫，长裤，背心，夹克，外套，短袜，鞋)	1.50	**Walking-1.8 m/s** (行走)	3.8

Day ()	**PART 1-THERMAL SURVEY in LIVING / [✓ BED] ROOM** (热舒适调研)							
Test 1	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)	-3	3	2	1.3	1	10.5 12.1	64.7%	0
Second Half (第二个半小时)	-3	3	3	1.3.	1	10.6 11.7	65.8%	0
Test 2	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)	-3	2	2	1.3	1.6	12.0 13.1	68.9%	0
Second Half (第二个半小时)	-3	2	2	1.3	1	12.1 13.2	66.8%	0
Test 3	**Thermal experience** (热体验评价)	**Overall comfort** (总体舒适感评价)	**Thermal tolerance** (热容忍评价)	**Cloth** (衣着状况)	**Activity** (活动状态)	**Air temperature** (空气温度)	**Relative humidity** (湿度)	**Air velocity** (风速)
First Half (第一个半小时)	-3	3	2	1.3	1	11.6 11	70.2%	0
Second Half (第二个半小时)	-3	3	2	1.3	1	11.5 11.8	69.2%	0

THE END

(问卷结束)

THANKS YOUR PARTICIPATION AND PATIENCE

(感谢您的耐心参与)

APPENDIX B – MATLAB PROGRAM OF PMV-PPD CALCULATION

B1: PMV PROGRAM:

```
%PMVF   Calculation of the Predicted Mean Vote (pmv) and the
%   Predicted Percentage of Dissatisfied (ppd) according
%   Fanger
%
% SYNOPSIS: [PMVOUT]=pmvf(PMVPAR)
%
% DESCRIPTION:
%  PMVPAR is a n-by-7 matrix which contains the input parameters
%  for calculating the pmv and ppd:
%   PMVPAR(:,1): metabolism [W/m^2]
%   PMVPAR(:,2): external work [W/m^2]
%   PMVPAR(:,3): radiant temperature [degree celsius]
%   PMVPAR(:,4): air temperatuur [degree celsius]
%   PMVPAR(:,5): relative humidity    [0 < Rh < 1]
%   PMVPAR(:,6): clothing [clo]
%   PMVPAR(:,7): air velocuty [m/s]
%
%  PMVOUT is a n-by-2 matrix containing in the first colum
%  the pmv values and in the second colum the ppd values.
%
% EXAMPLE:
%
%  PMVVAR=[58.2 0 20 20 0.5 1 0.2;58.2 0 20 20 0.5 1 0.3];
%  [PMVOUT]=pmvf(PMVVAR)
%
%  PMVOUT =
%
%   -1.1337   32.0718
%   -1.2965   40.0881
%
% SEE ALSO: ppdf
%
% REFERENCE: Jellema 7a,
%
% MFILES REQUIRED: pmveqf, ppdf
%
% AUTEUR/DATE: JvS/1998/03
%




function q = pmvf(in)

insize = size(in);

% q = zeros(insize(1),2);
```

```
if insize(2) == 7
    q = zeros(insize(1), 2);
for i = 1:insize(1)
        pm = in(i,:);
        uu11 = pm;
        pm(6) = pm(6)*0.155;
if pm(6) <= 0.078,
            fclpmv = 1+1.29*pm(6);
else
            fclpmv = 1.05+0.645*pm(6);
end
        pm(8) = fclpmv;
        x = fminsearch('pmveqf',[30 30]',[],pm);

        tclpmv = x(1);
        hcpmv = x(2);
        pm = uu11;
        q1 = (0.303*exp(-0.036*pm(1))+0.028);
        q(i,1) = q1 * (pm(1) - pm(2) - ...
                        3.05e-3*(5733-6.99*(pm(1)-pm(2))-pm(5)*psatf(pm(4))) - ...
                        0.42*(pm(1)-pm(2)-58.15) - ...
                        1.7e-5*pm(1)*(5867-pm(5)*psatf(pm(4))) - ...
                        0.0014*pm(1)*(34-pm(4)) - ...
                        3.96e-8*fclpmv*( (tclpmv+273)^4 -(pm(3)+273)^4 ) - ...
                        fclpmv*hcpmv*(tclpmv-pm(4)));
        q(i,2) = ppdf(q(i,1));
end

else
    disp('Wrong inputmatrix. Inputmatrix must be: n-by-7 ')
    disp('CALCULATION INTERRUPTED !')
    q = [];

end
```

B2: PPD PROGRAM:

```
% PPDF Predicted Percentage of Dissatisfied [%]
%     Gebruik: ppd(x) met x=PMV
%
%     Voorbeeld:
%
%  ppd(1)
%
%  answer =
%
%  26.1197


function q = ppdf(x)
q = 100 - 95*exp(-0.2179*x.^2 - 0.03353*x.^4);
```

B3: PMV-PPD MAIN PROGRAM:

```
function varargout = PMVmain(varargin)
% PMVMAIN MATLAB code for PMVmain.fig
%      PMVMAIN, by itself, creates a new PMVMAIN or raises the existing
%      singleton*.
%
%      H = PMVMAIN returns the handle to a new PMVMAIN or the handle to
%      the existing singleton*.
%
%      PMVMAIN('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in PMVMAIN.M with the given uipanelinput arguments.
%
%      PMVMAIN('Property','Value',...) creates a new PMVMAIN or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before PMVmain_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to PMVmain_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help PMVmain

% Last Modified by GUIDE v2.5 14-Mar-2012 11:20:06

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
```

```
gui_State = struct('gui_Name',       mfilename, ...
'gui_Singleton',  gui_Singleton, ...
'gui_OpeningFcn', @PMVmain_OpeningFcn, ...
'gui_OutputFcn',  @PMVmain_OutputFcn, ...
'gui_LayoutFcn',  [] , ...
'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before PMVmain is made visible.
function PMVmain_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to PMVmain (see VARARGIN)

% Set the UITable as invisible
set(handles.uitableexcel, 'Visible', 'off','Enable', 'off');
% set(handles.pushbuttonman, 'Enable', 'off');
set(handles.pushbuttonimportexcel, 'Enable', 'off');

set(handles.uitableexcel, 'Data', []);

set(gcf, 'UserData', []);

% Choose default command line output for PMVmain
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);



% UIWAIT makes PMVmain wait for user response (see UIRESUME)
% uiwait(handles.pmvmain);


% --- Outputs from this function are returned to the command line.
function varargout = PMVmain_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
```

```
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


% --- Executes on button press in pushbuttoncal.
function pushbuttoncal_Callback(hObject, eventdata, handles)
% hObject    handle to pushbuttoncal (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

isexcel = strcmp(get(handles.pushbuttonimportexcel, 'Enable'), 'on');

if ~isexcel

% Get the values of inputs
   clo = get(handles.editclo, 'String');
if isempty(clo)
      herr = errordlg('You must enter a numeric value', ...
'Bad Clothing Value','modal');
      uiwait(herr);
      uicontrol(handles.editclo);
return
else
      clo = str2double(clo);
if isnan(clo)
         herr = errordlg('You must enter a numeric value', ...
'Bad Clothing Value','modal');
         uiwait(herr);
         uicontrol(handles.editclo);
return
end
end

   met = get(handles.editmet, 'String');
if isempty(met)
      herr = errordlg('You must enter a numeric value', ...
'Bad MET Value','modal');
      uiwait(herr);
      uicontrol(handles.editmet);
return
else
      met = str2double(met);
if isnan(met)
         herr = errordlg('You must enter a numeric value', ...
'Bad MET Value','modal');
         uiwait(herr);
         uicontrol(handles.editmet);
return
```

```
end
end

    wme = get(handles.editwme, 'String');
if isempty(wme)
        herr = errordlg('You must enter a numeric value', ...
'Bad WME Value','modal');
        uiwait(herr);
        uicontrol(handles.editwme);
return
else
        wme = str2double(wme);
if isnan(wme)
            herr = errordlg('You must enter a numeric value', ...
'Bad WME Value','modal');
            uiwait(herr);
            uicontrol(handles.editwme);
return
end
end

    ta = get(handles.editta, 'String');
if isempty(ta)
        herr = errordlg('You must enter a numeric value', ...
'Bad TA Value','modal');
        uiwait(herr);
        uicontrol(handles.editta);
return
else
        ta = str2double(ta);
if isnan(ta)
            herr = errordlg('You must enter a numeric value', ...
'Bad TA Value','modal');
            uiwait(herr);
            uicontrol(handles.editta);
return
end
end

    tr = get(handles.edittr, 'String');
if isempty(tr)
        herr = errordlg('You must enter a numeric value', ...
'Bad TR Value','modal');
        uiwait(herr);
        uicontrol(handles.edittr);
return
else
        tr = str2double(tr);
if isnan(tr)
            herr = errordlg('You must enter a numeric value', ...
'Bad TR Value','modal');
```

```
            uiwait(herr);
            uicontrol(handles.edittr);
return
end
end

    vel = get(handles.editvel, 'String');
if isempty(vel)
        herr = errordlg('You must enter a numeric value', ...
'Bad VEL Value','modal');
        uiwait(herr);
        uicontrol(handles.editvel);
return
else
        vel = str2double(vel);
if isnan(vel)
            herr = errordlg('You must enter a numeric value', ...
'Bad VEL Value','modal');
            uiwait(herr);
            uicontrol(handles.editvel);
return
end
end

if get(handles.radiobuttonsat, 'Value') == get(handles.radiobuttonsat, 'Max')
        sat = get(handles.editsat, 'String');
if isempty(sat)
            herr = errordlg('You must enter a numeric value', ...
'Bad SAT Value','modal');
            uiwait(herr);
            uicontrol(handles.editsat);
return
else
            sat = str2double(sat);
if isnan(sat)
                herr = errordlg('You must enter a numeric value', ...
'Bad SAT Value','modal');
                uiwait(herr);
                uicontrol(handles.editsat);
return
end
end
end

if get(handles.radiobuttonps, 'Value') == get(handles.radiobuttonps, 'Max')
        ps = get(handles.editps, 'String');
if isempty(ps)
            herr = errordlg('You must enter a numeric value', ...
'Bad PS Value','modal');
            uiwait(herr);
            uicontrol(handles.editps);
```

```
return
else
      ps = str2double(ps);
if isnan(ps)
        herr = errordlg('You must enter a numeric value', ...
'Bad PS Value','modal');
        uiwait(herr);
        uicontrol(handles.editps);
return
end
end
end

if ~exist('ps', 'var')
    ps = sat * 10 * exp((16.6536-4030.183)/(ta+235));
end

if ~exist('sat', 'var')
    sat = ps / (10 * exp((16.6536-4030.183)/(ta+235)));
end

  PMVPAR = [58*met 58*wme tr ta sat/100 clo vel];
%  for calculating the pmv and ppd:
%   PMVPAR(:,1): metabolism [W/m^2]
%   PMVPAR(:,2): external work [W/m^2]
%   PMVPAR(:,3): radiant temperature [degree celsius]
%   PMVPAR(:,4): air temperatuur [degree celsius]
%   PMVPAR(:,5): relative humidity    [0 < Rh < 1]
%   PMVPAR(:,6): clothing [clo]
%   PMVPAR(:,7): air velocuty [m/s]

  PMVOUT = pmvf(PMVPAR);

  strPMV = sprintf('%0.3G', PMVOUT(1));
  strPPD = sprintf('%0.3G %%', PMVOUT(2));

  set(handles.textPMVvalue, 'String', strPMV);
  set(handles.textPPDvalue, 'String', strPPD);

else
  PMVdata = get(gcf, 'UserData');
if ~isempty(PMVdata)
    PMVPAR = zeros(size(PMVdata.data,1), 7);
    PMVPAR(:,1) = PMVdata.data(:,2) * 58;
    PMVPAR(:,2) = PMVdata.data(:,3) * 58;
    PMVPAR(:,3) = PMVdata.data(:,5);
    PMVPAR(:,4) = PMVdata.data(:,4);
    PMVPAR(:,5) = PMVdata.data(:,7);
    PMVPAR(:,6) = PMVdata.data(:,1);
    PMVPAR(:,7) = PMVdata.data(:,6);
```

```
% sat = ps / (10 * exp((16.6536-4030.183)/(ta+235)));
% Calulate sat when they are unavailable (ps available)
if any(isnan(PMVPAR(:,5)))
      PMVPAR(isnan(PMVPAR(:,5)),5) = ...
        PMVdata.data(isnan(PMVPAR(:,5)),8) ./ ...
        (10 * exp((16.6536-4030.183)/(PMVdata.data(isnan(PMVPAR(:,5)),4)+235)));
else
if size(PMVdata.data, 2) == 7
        PMVdata.data(:,8) = NaN;
end
end

% PMVPAR(:,5) = PMVPAR(:,5) / 100;

    PMVdata.resultdata = pmvf(PMVPAR);

    PMVdata.resultdata(:,2) = PMVdata.resultdata(:,2) / 100;

    tabledata = cell(size(PMVdata.data,1), 11);
    tabledata(:, 1:size(PMVdata.data,2)) = num2cell(PMVdata.data);
    tabledata(:, (size(PMVdata.data,2)+2):end) = ...
      num2cell(PMVdata.resultdata);

    set(handles.uitableexcel, 'Data', tabledata);
    set(gcf, 'UserData', PMVdata);

% * Preparing export data
    exportdata = cell(size(tabledata,1)+1,size(tabledata,2));
    PMVdata.colheaders{8} = 'Vapour pressure';
    PMVdata.colheaders{9} = '';
    PMVdata.colheaders{10} = 'PMV';
    PMVdata.colheaders{11} = 'PPD';
    exportdata(1,:) = PMVdata.colheaders;
    exportdata(2:end, :) = tabledata;


    inputfilename = PMVdata.datafilename;

if exist(inputfilename, 'file')
      [pathstr, name, ext] = fileparts(inputfilename);

if ismac
        outputfilename = fullfile(pathstr, [name, '-result', '.csv']);
        dlmcell(outputfilename, exportdata, ',');
else
        outputfilename = fullfile(pathstr, [name, '-result', ext]);
        xlswrite(outputfilename, exportdata, 'Result', 'A1');

end

end
```

```
end
end



% --- Executes on button press in pushbuttonreset.
function pushbuttonreset_Callback(hObject, eventdata, handles)
% hObject    handle to pushbuttonreset (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

set(handles.editclo, 'String', '');
set(handles.editmet, 'String', '');
set(handles.editwme, 'String', '');
set(handles.editta, 'String', '');
set(handles.edittr, 'String', '');
set(handles.editvel, 'String', '');
set(handles.editsat, 'Enable', 'on', 'String', '');
set(handles.editps, 'Enable', 'off', 'String', '');
set(handles.textPMVvalue, 'String', '999999!');
set(handles.textPPDvalue, 'String', '100 %');

set(handles.radiobuttonsat, 'Value', get(handles.radiobuttonsat, 'Max'));
set(handles.radiobuttonps, 'Value', get(handles.radiobuttonps, 'Min'));

set(handles.uitableexcel, 'Data', []);
set(gcf, 'UserData', []);



% uicontrol(handles.editclo);





% --- Executes on button press in pushbuttonquit.
function pushbuttonquit_Callback(hObject, eventdata, handles)
% hObject    handle to pushbuttonquit (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

delete(handles.pmvmain);



function editclo_Callback(hObject, eventdata, handles)
% hObject    handle to editclo (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editclo as text
```

```
%       str2double(get(hObject,'String')) returns contents of editclo as a double


% --- Executes during object creation, after setting all properties.
function editclo_CreateFcn(hObject, eventdata, handles)
% hObject    handle to editclo (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function editmet_Callback(hObject, eventdata, handles)
% hObject    handle to editmet (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editmet as text
%       str2double(get(hObject,'String')) returns contents of editmet as a double


% --- Executes during object creation, after setting all properties.
function editmet_CreateFcn(hObject, eventdata, handles)
% hObject    handle to editmet (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function editwme_Callback(hObject, eventdata, handles)
% hObject    handle to editwme (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editwme as text
%       str2double(get(hObject,'String')) returns contents of editwme as a double


% --- Executes during object creation, after setting all properties.
function editwme_CreateFcn(hObject, eventdata, handles)
```

```
% hObject    handle to editwme (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function editta_Callback(hObject, eventdata, handles)
% hObject    handle to editta (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editta as text
%        str2double(get(hObject,'String')) returns contents of editta as a double


% --- Executes during object creation, after setting all properties.
function editta_CreateFcn(hObject, eventdata, handles)
% hObject    handle to editta (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edittr_Callback(hObject, eventdata, handles)
% hObject    handle to edittr (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edittr as text
%        str2double(get(hObject,'String')) returns contents of edittr as a double


% --- Executes during object creation, after setting all properties.
function edittr_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edittr (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
```

```
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function editvel_Callback(hObject, eventdata, handles)
% hObject    handle to editvel (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editvel as text
%        str2double(get(hObject,'String')) returns contents of editvel as a double


% --- Executes during object creation, after setting all properties.
function editvel_CreateFcn(hObject, eventdata, handles)
% hObject    handle to editvel (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function editsat_Callback(hObject, eventdata, handles)
% hObject    handle to editsat (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editsat as text
%        str2double(get(hObject,'String')) returns contents of editsat as a double


% --- Executes during object creation, after setting all properties.
function editsat_CreateFcn(hObject, eventdata, handles)
% hObject    handle to editsat (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function editps_Callback(hObject, eventdata, handles)
% hObject    handle to editps (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of editps as text
%        str2double(get(hObject,'String')) returns contents of editps as a double


% --- Executes during object creation, after setting all properties.
function editps_CreateFcn(hObject, eventdata, handles)
% hObject    handle to editps (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in radiobuttonsat.
function radiobuttonsat_Callback(hObject, eventdata, handles)
% hObject    handle to radiobuttonsat (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of radiobuttonsat

if (get(hObject,'Value') == get(hObject,'Max'))
    set(handles.editsat, 'Enable', 'on', 'String', '');
    set(handles.editps, 'Enable', 'off', 'String', '');
end


% --- Executes on button press in radiobuttonps.
function radiobuttonps_Callback(hObject, eventdata, handles)
% hObject    handle to radiobuttonps (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of radiobuttonps

if (get(hObject,'Value') == get(hObject,'Max'))
    set(handles.editsat, 'Enable', 'off', 'String', '');
    set(handles.editps, 'Enable', 'on', 'String', '');
end
```

```
% --- Executes on button press in pushbuttonimportexcel.
function pushbuttonimportexcel_Callback(hObject, eventdata, handles)
% hObject    handle to pushbuttonimportexcel (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

import com.mathworks.mlwidgets.workspace.ImportFileChooser;
% uiimport('-file');
fileAbsolutePath = '';
fileSelected = '';
javaMethodEDT('showImportFileDialog', ...
'com.mathworks.mlwidgets.workspace.ImportFileChooser', []);
if ImportFileChooser.getState() == javax.swing.JFileChooser.APPROVE_OPTION
   fileSelected = ImportFileChooser.getSelectedFile;
end
if (isempty(fileSelected))
%     if nargout > 0
%         varargout{1} = [];
%     end
return;
else
   fileAbsolutePath = char(fileSelected.getAbsolutePath);
end
isSynchronous = true;
if useAlternateImportTool(isSynchronous,fileAbsolutePath)
%     if nargout > 0
%         varargout{1} = [];
%     end
return;
end

ctorFile = java.io.File(fileAbsolutePath);

% Detect and report empty input files - display an error dialog
if ctorFile.length == 0
   javaMethodEDT('showMessageDialog', ...
'com.mathworks.mwswing.MJOptionPane', [], ...
       xlate('Cannot import from an empty input file'), ...
       xlate('Import Wizard'), 0);
return;
end

type = finfo(fileAbsolutePath);

if ismac && (~strcmpi(type, 'xls'))
   errordlg('Only xls files (Excel 97-2004) are acceptable on Mac OS!!!');
return
end
```

```
if ispc && (~(strcmpi(type, 'xls') || strcmpi(type, 'xlsx') || ...
            strcmpi(type, 'xlsm') || strcmpi(type, 'xlsb') ...
            || strcmpi(type, 'csv')))
    errordlg('Only xls, xlsx or csv files are acceptable on Windows!!!');
return
end

PMVdata = [];
if exist(fileAbsolutePath, 'file')
    PMVdata = importdata(fileAbsolutePath);
else
    errordlg('Data file doesn''t exist!!!');
end

if ~isempty(PMVdata)
    set(handles.uitableexcel, 'Data', PMVdata.data);
    PMVdata.datafilename = fileAbsolutePath;
%     get(gcf, 'UserData')
    set(gcf, 'UserData', PMVdata);
end

% PMVPAR = [58*met 58*wme tr ta sat/100 clo vel];

function rerouted = useAlternateImportTool(isSynchronous,fn)
rerouted = false;
if ~isempty (fn)
    type = finfo(fn);
if ~isSynchronous && (strcmpi(type, 'xls') || strcmpi(type, 'xlsx') || ...
            strcmpi(type, 'xlsm') || strcmpi(type, 'xlsb') ...
            || strcmpi(type, 'csv')) || strcmpi(type, 'ods')
        com.mathworks.mlwidgets.importtool.SpreadsheetImportClient.open(fn);
        rerouted = true;
elseif ishdf(fn)
        rerouted = true;
        hdftool(fn);
end
end

function ret = ishdf(file)
out = [];
fid = fopen(file);
if fid ~= -1
    out = fread(fid, 4);
    fclose(fid);
end
ret = length(out) == 4 && sum(out == [14; 3; 19; 1]) == 4;


% --- Executes when selected object is changed in uipanelswitcher.
function uipanelswitcher_SelectionChangeFcn(hObject, eventdata, handles)
% hObject    handle to the selected object in uipanelswitcher
```

```
% eventdata  structure with the following fields (see UIBUTTONGROUP)
%   EventName: string 'SelectionChanged' (read only)
%   OldValue: handle of the previously selected object or empty if none was selected
%   NewValue: handle of the currently selected object
% handles    structure with handles and user data (see GUIDATA)

switch get(eventdata.NewValue,'String')
case'Manually'
        set(handles.pushbuttonimportexcel, 'Enable', 'off');
%         set(handles.pushbuttonman, 'Enable', 'on');

        set(handles.uitableexcel, 'Visible', 'off','Enable', 'off');

        set(handles.uipanelinput, 'Visible', 'on');
        set(handles.uipaneloutput, 'Visible', 'on');


case'Excel'
        set(handles.pushbuttonimportexcel, 'Enable', 'on');
%         set(handles.pushbuttonman, 'Enable', 'off');

        set(handles.uitableexcel, 'Visible', 'on','Enable', 'on');


        set(handles.uipanelinput, 'Visible', 'off');
        set(handles.uipaneloutput, 'Visible', 'off');


otherwise
return
end
```

APPENDIX C–STATISTICAL CORELATION AND SIGNIFICANCE TEST

C1: TEST OF CASE A FOR SUMMER FIELD STUDY

365 SAMPLES		Clo	Metabolic rate	AMV	Oc	Tt	Actual PMV	Actual PPD	T_i	T_{mrt}	V_i	RH
Clo	Pearson Correlation	1	.030	-.122*	-.330**	-.363**	-.303**	-.306**	-.470**	-.485**	.066	.330**
	Sig. (2-tailed)		.572	.020	.000	.000	.000	.000	.000	.000	.206	.000
Metabolic rate	Pearson Correlation	.030	1	.309**	.120*	.096	.379**	.307**	-.054	-.028	.046	.143**
	Sig. (2-tailed)	.572		.000	.021	.067	.000	.000	.300	.593	.382	.006
AMV	Pearson Correlation	-.122*	.309**	1	.557**	.549**	.624**	.580**	.514**	.525**	-.075	-.144**
	Sig. (2-tailed)	.020	.000		.000	.000	.000	.000	.000	.000	.151	.006
Oc	Pearson Correlation	-.330**	.120*	.557**	1	.812**	.534**	.499**	.568**	.616**	.064	-.299**
	Sig. (2-tailed)	.000	.021	.000		.000	.000	.000	.000	.000	.222	.000
Tt	Pearson Correlation	-.363**	.096	.549**	.812**	1	.518**	.482**	.567**	.608**	.059	-.306**
	Sig. (2-tailed)	.000	.067	.000	.000		.000	.000	.000	.000	.265	.000
Actual PMV	Pearson Correlation	-.303**	.379**	.624**	.534**	.518**	1	.976**	.832**	.816**	-.274**	-.322**
	Sig. (2-tailed)	.000	.000	.000	.000	.000		.000	.000	.000	.000	.000
Actual PPD	Pearson Correlation	-.306**	.307**	.580**	.499**	.482**	.976**	1	.835**	.801**	-.298**	-.321**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000		.000	.000	.000	.000
T_i	Pearson Correlation	-.470**	-.054	.514**	.568**	.567**	.832**	.835**	1	.942**	-.165**	-.486**
	Sig. (2-tailed)	.000	.300	.000	.000	.000	.000	.000		.000	.002	.000
T_{mrt}	Pearson Correlation	-.485**	-.028	.525**	.616**	.608**	.816**	.801**	.942**	1	-.141**	-.534**
	Sig. (2-tailed)	.000	.593	.000	.000	.000	.000	.000	.000		.007	.000
V_i	Pearson Correlation	.066	.046	-.075	.064	.059	-.274**	-.298**	-.165**	-.141**	1	.108*
	Sig. (2-tailed)	.206	.382	.151	.222	.265	.000	.000	.002	.007		.039
RH	Pearson Correlation	.330**	.143**	-.144**	-.299**	-.306**	-.322**	-.321**	-.486**	-.534**	.108*	1
	Sig. (2-tailed)	.000	.006	.006	.000	.000	.000	.000	.000	.000	.039	

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

C2: TEST OF CASE B FOR SUMMER FIELD STUDY

362 SAMPLES		**Clo**	**Metabolic rate**	**AMV**	**Oc**	**Tt**	**Actual PMV**	**Actual PPD**	**T_i**	**T_{mrt}**	**V_i**	**RH**
Clo	Pearson Correlation	1	.095	.199**	.160**	.104*	.232**	.258**	.229**	.234**	.109*	-.037
	Sig. (2-tailed)		.070	.000	.002	.048	.000	.000	.000	.000	.038	.481
Metabolic rate	Pearson Correlation	.095	1	.605**	.414**	.401**	.655**	.681**	.317**	.304**	-.088	.211**
	Sig. (2-tailed)	.070		.000	.000	.000	.000	.000	.000	.000	.094	.000
AMV	Pearson Correlation	.199**	.605**	1	.595**	.560**	.711**	.726**	.592**	.590**	-.157**	.150**
	Sig. (2-tailed)	.000	.000		.000	.000	.000	.000	.000	.000	.003	.004
Oc	Pearson Correlation	.160**	.414**	.595**	1	.837**	.700**	.701**	.688**	.686**	-.254**	.185**
	Sig. (2-tailed)	.002	.000	.000		.000	.000	.000	.000	.000	.000	.000
Tt	Pearson Correlation	.104*	.401**	.560**	.837**	1	.629**	.634**	.631**	.633**	-.201**	.178**
	Sig. (2-tailed)	.048	.000	.000	.000		.000	.000	.000	.000	.000	.001
Actual PMV	Pearson Correlation	.232**	.655**	.711**	.700**	.629**	1	.956**	.780**	.794**	-.457**	.141**
	Sig. (2-tailed)	.000	.000	.000	.000	.000		.000	.000	.000	.000	.007
Actual PPD	Pearson Correlation	.258**	.681**	.726**	.701**	.634**	.956**	1	.796**	.822**	-.303**	.209**
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000		.000	.000	.000	.000
T_i	Pearson Correlation	.229**	.317**	.592**	.688**	.631**	.780**	.796**	1	.955**	-.151**	-.024
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000		.000	.004	.647
T_{mrt}	Pearson Correlation	.234**	.304**	.590**	.686**	.633**	.794**	.822**	.955**	1	-.180**	.000
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000		.001	.996
V_i	Pearson Correlation	.109*	-.088	-.157**	-.254**	-.201**	-.457**	-.303**	-.151**	-.180**	1	.030
	Sig. (2-tailed)	.038	.094	.003	.000	.000	.000	.000	.004	.001		.571
RH	Pearson Correlation	-.037	.211**	.150**	.185**	.178**	.141**	.209**	-.024	.000	.030	1
	Sig. (2-tailed)	.481	.000	.004	.000	.001	.007	.000	.647	.996	.571	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

C3: TEST OF CASE A FOR WINTER FIELD STUDY

352 SAMPLES		**Clo**	**Metabolic rate**	**AMV**	**Oc**	**Tt**	**Actual PMV**	**Actual PPD**	**T_i**	**T_{mrt}**	**V_i**	**RH**
Clo	Pearson Correlation	1	.273**	-.019	-.022	.021	-.019	.019	-.012	-.023	-.491**	-.028
	Sig. (2-tailed)		.000	.717	.683	.698	.719	.722	.820	.668	.000	.596
Metabolic rate	Pearson Correlation	.273**	1	.028	.003	.053	.005	-.009	.018	.004	.005	-.106*
	Sig. (2-tailed)	.000		.601	.951	.321	.932	.866	.738	.946	.920	.047
AMV	Pearson Correlation	-.019	.028	1	-.623**	-.559**	.796**	-.798**	.795**	.784**	.052	-.160**
	Sig. (2-tailed)	.717	.601		.000	.000	.000	.000	.000	.000	.334	.003
Oc	Pearson Correlation	-.022	.003	-.623**	1	.791**	-.761**	.763**	-.758**	-.748**	-.043	.125*
	Sig. (2-tailed)	.683	.951	.000		.000	.000	.000	.000	.000	.421	.019
Tt	Pearson Correlation	.021	.053	-.559**	.791**	1	-.717**	.705**	-.706**	-.694**	-.055	.009
	Sig. (2-tailed)	.698	.321	.000	.000		.000	.000	.000	.000	.300	.866
Actual PMV	Pearson Correlation	-.019	.005	.796**	-.761**	-.717**	1	-.995**	.992**	.985**	.043	-.144**
	Sig. (2-tailed)	.719	.932	.000	.000	.000		.000	.000	.000	.416	.007
Actual PPD	Pearson Correlation	.019	-.009	-.798**	.763**	.705**	-.995**	1	-.988**	-.980**	-.043	.155**
	Sig. (2-tailed)	.722	.866	.000	.000	.000	.000		.000	.000	.422	.003
T_i	Pearson Correlation	-.012	.018	.795**	-.758**	-.706**	.992**	-.988**	1	.966**	.034	-.219**
	Sig. (2-tailed)	.820	.738	.000	.000	.000	.000	.000		.000	.520	.000
T_{mrt}	Pearson Correlation	-.023	.004	.784**	-.748**	-.694**	.985**	-.980**	.966**	1	.034	-.219**
	Sig. (2-tailed)	.668	.946	.000	.000	.000	.000	.000	.000		.523	.000
V_i	Pearson Correlation	-.491**	.005	.052	-.043	-.055	.043	-.043	.034	.034	1	.100
	Sig. (2-tailed)	.000	.920	.334	.421	.300	.416	.422	.520	.523		.062
RH	Pearson Correlation	-.028	-.106*	-.160**	.125*	.009	-.144**	.155**	-.219**	-.219**	.100	1
	Sig. (2-tailed)	.596	.047	.003	.019	.866	.007	.003	.000	.000	.062	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

C4: TEST OF CASE B FOR WINTER FIELD STUDY

292 SAMPLES		**Clo**	**Metabolic rate**	**AMV**	**Oc**	**Tt**	**Actual PMV**	**Actual PPD**	**T_i**	**T_{mrt}**	**V_i**	**RH**
Clo	Pearson Correlation	1	.232**	.080	-.110	-.122*	.107	-.089	.110	.125*	.008	-.104
	Sig. (2-tailed)		.000	.171	.060	.037	.067	.131	.061	.033	.897	.076
Metabolic rate	Pearson Correlation	.232**	1	.004	.050	.059	.103	-.094	.086	.108	.009	.084
	Sig. (2-tailed)	.000		.943	.393	.317	.079	.108	.141	.064	.875	.151
AMV	Pearson Correlation	.080	.004	1	-.512**	-.543**	.729**	-.673**	.739**	.715**	-.014	.003
	Sig. (2-tailed)	.171	.943		.000	.000	.000	.000	.000	.000	.810	.962
Oc	Pearson Correlation	-.110	.050	-.512**	1	.677**	-.513**	.513**	-.529**	-.546**	-.056	.257**
	Sig. (2-tailed)	.060	.393	.000		.000	.000	.000	.000	.000	.341	.000
Tt	Pearson Correlation	-.122*	.059	-.543**	.677**	1	-.639**	.567**	-.649**	-.641**	.002	.076
	Sig. (2-tailed)	.037	.317	.000	.000		.000	.000	.000	.000	.975	.193
Actual PMV	Pearson Correlation	.107	.103	.729**	-.513**	-.639**	1	-.937**	.991**	.978**	-.020	.160**
	Sig. (2-tailed)	.067	.079	.000	.000	.000		.000	.000	.000	.737	.006
Actual PPD	Pearson Correlation	-.089	-.094	-.673**	.513**	.567**	-.937**	1	-.929**	-.925**	.034	-.090
	Sig. (2-tailed)	.131	.108	.000	.000	.000	.000		.000	.000	.559	.125
T_i	Pearson Correlation	.110	.086	.739**	-.529**	-.649**	.991**	-.929**	1	.958**	-.005	.092
	Sig. (2-tailed)	.061	.141	.000	.000	.000	.000	.000		.000	.931	.116
T_{mrt}	Pearson Correlation	.125*	.108	.715**	-.546**	-.641**	.978**	-.925**	.958**	1	-.002	.038
	Sig. (2-tailed)	.033	.064	.000	.000	.000	.000	.000	.000		.966	.523
V_i	Pearson Correlation	.008	.009	-.014	-.056	.002	-.020	.034	-.005	-.002	1	-.172**
	Sig. (2-tailed)	.897	.875	.810	.341	.975	.737	.559	.931	.966		.003
RH	Pearson Correlation	-.104	.084	.003	.257**	.076	.160**	-.090	.092	.038	-.172**	1
	Sig. (2-tailed)	.076	.151	.962	.000	.193	.006	.125	.116	.523	.003	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

APPENDIX D – PUBLICATIONS

D1: LIST OF PUBLICATIONS:

1. Wang, X. and Altan,H. (2011), "*The Thermal Performance Evaluation of Future Chinese Low-energy Apartments within Changing Climate in 'Hot Summer and Cold Winter' Climatic Zone in China*", 12th Conference of International Building Performance Simulation Association (BS 2011), 14th-16th November 2011, Sydney, Australia, Proceedings, pp.2738-2745, IBPSA Australasia and AIRAH, ISBN: 978-0-646-56510-1.

2. Wang, X. and Altan,H. (2011), "*Investigation into current Chinese Low Energy Buildings and the Thermal Comfort Conditions in Hot Summer and Cold Winter Climatic Zone in China*", 10th International Conference on Sustainable Energy Technologies (SET2011), 4th-7th September 2011, İstanbul, Turkey, Proceedings, ISBN: 978-605-88549-1-8.

3. Wang, X. and Altan,H. (2011),"*Investigation of the Thermal Comfort Theory Extension in Chinese Low-energy Dwellings in Hot Summer and Cold Winter (HSCW) Zone*", 9th China Urban Housing Conference (CHI 2011) on Low Carbon Green City and Harmonious Habitat Society, 8th-9th July 2011, Hong Kong, China, China Architecture & Building Press, Proceedings, pp. 523-530, ISBN: 978-7-112-13319-2, (Received Best Paper Award).

4. Wang, X. and Altan,H.and Kang,J. (2010), "*A New Approach for Energy Efficiency in Chinese Apartments*", The 9th International Conference on Sustainable Energy Technologies (SET 2010), 24th-27thAugust 2010, Shanghai, China, Proceedings.

5. Wang, X. and Altan,H. (2009), "*Urbanism, Mixture of Sustainability, Technology, and Culture: Case of Off-Grid City, South Korea, 2009*", 9th UK CARE Annual General Meeting, 5th September 2009, Salford, Great Manchester, UK, ISBN-13: 978-0-9551965-5-3.

(D1-1)THE THERMAL PERFORMANCE EVALUATION OF A FUTURE CHINESE LOW-ENERGY APARTMENT WITHIN CHANGING CLIMATE IN 'HOT SUMMER AND COLD WINTER' ZONE IN CHINA

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ABSTRACT

The paper aims to evaluate the thermal performance of a typical Chinese low-energy residential building in 'Hot Summer and Cold Winter' zone where two prototypes within a six-storey healthy housing with low-energy standards have been investigated. According to the building simulation study undertaken, prototype 1 has relatively good thermal performance compared to prototype 2. In the study, the low-energy parameters have been taken into consideration for both prototypes as an input, which is defined as an energy efficiency building code in HSCW zone with an insulated construction and a criterion calculating indoor temperatures. The simulation resultshave shown that the existing Chinese low-energy building design standard cannot achieve the thermal comfort requirement introduced bytheASHREA 55-2004 standard. Furthermore in the study, the adjustment mechanism of occupancyfor thermal comfort has been incorporated with the simulation studies. Moreover, the regional thermal sensation measurementshave proven that it is important to consider both thermal comfort and low-energy building studies together.

INTRODUCTION

The risk of global warming and providing a healthy housing is essential which is also confirmed by the Chinese government policy of energy saving and low-carbon emissionscode toencourage a further research challenge. In China, energy saving target of 50% (MHURD 2003)reduction in new buildings compared with the level in the duration between 1980-1981 has been clearly targetted in the last national development strategy(MHURD 2006) of the 11th 'Five-year Plan' (2005-2010). Moreover, a higher aim of energy saving is established for the detailed discussion in the 12th 'Five-year Plan' (2011-2015).

CHINESERESIDENTIAL BUILDING

The common residential housing is classified in four sections by Chinese official legislation(MHURD 2006), respectively including indemnificatory housing with the floor area around 40-60 m^2, economically affordable housing limited around 60-80m^2, comfortable housing limited around 80-100m^2 and rural housing which is around 120-150m^2. This official classification has been mentioned in the outline of 11th 'Five-Year Plans on Civil Construction Issues, 2006'. Healthy housing has been defined with the minimum limit of available floor area in a current residential building unit in 2004 (CNERCHS 2004). The minimum limit values of available floor area have been listed below in Table 1.

Table 1
The minimum limit of available floor area in a Chinese apartment unit

UNIT SPACE	The minimum limit area (m^2)
LIVING ROOM	16.20 (3.6mx4.5m)
DINING SPACE	7.20 (3.0mx2.4m)
MAIN BEDROOM	13.86 (3.3mx4.2m)
SUB BEDROOM (DOUBLE BED)	11.70 (3.0mx3.9m)
KITCHEN (SINGLE LAYOUT)	5.55 (1.5mx3.7m)
TOILET	4.50 (1.8mx2.5m)

Building Layout

According to the Chinese healthy housing technical essential code, a series of indoor floor area has been defined in six spaces. Two kinds of apartments have been investigated in this paper, which are totally defined at minimum floor area limit. Moreover these two testing unit are respectively combined in a six-storey building, which is frequently designed to be common prototypes in China. In a detail layout, prototype 1 is defined to be a rectangle shape with short faces towards north-south orientation, and prototype 2 has a square shape with as same direction as prototype 1. Figure 1 displays the prototypesused for simulation studies.

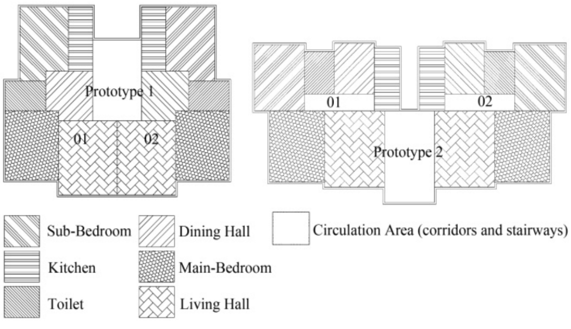

Figure 1 Layout of two prototypes

(D1-2) AN INVESTIGATION INTO CURRENT CHINESE LOW-ENERGY BUILDINGS AND THERMAL COMFORT CONDITIONS IN HOT SUMMER AND COLD WINTER CLIMATIC ZONE IN CHINA

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Abstract:

Following the rapid economic development in today's China, the low-energy building standard has become essential when considering sustainable energy technologies within the residential building environment. Chinese national legislation and building research is paying more attention to energy savings using construction renovation, envelope insulation materials in extreme climate conditions, energy efficiency of appliances and even operational schedules for occupant activities. However, achieving building thermal comfort is not necessarily an easy target with low energy target set in the Chinese 'five-year plan', which puts forward more critical aims of energy savings from the beginning of new century. Simulation work using DesignBuilder has been carried out to express the comfortable period in a current Chinese low-energy building. Two apartment prototypes are modelled for the building simulation study, which is also based on the healthy housing technical essential. The outcome achieved for heating and cooling design on thermal performance of a low-energy building was not very positive and the findings have shown that an insulated external wall construction cannot satisfy all the thermal comfort potentials.

Keywords:

Low-energy building, thermal comfort, computer simulation, overheating, HSCW zone

1. Introduction

In the process of the China 'Reform and Opening-up'[1], the basic description of living environment has various appearances. The common residential buildings are distributed in many approaches, which enrich the urban property purchase in Chinese residential building market and take care for low-income group by welfare of China harmonious society. Common residential community is a kind of gathering living in China. Lots of apartment blocks are built in piece of area with artificial landscape. These buildings are defined by residential building market, and then the commercial values are fluctuated with land prices. Almost common residential buildings are distributed by commodity exchange in the housing market. Chinese common residential building is multiple storey block [2] based on the quantity of vertical elevators. The common prototype is apartment style and energy efficiency strategy is chosen to face the huge energy burden in the fast developing China. At the same time, the indoor thermal comfort is focused with the growth of living situations by local government. Therefore, the investigation of the new generation residential building is a significant research [3, 4] in today's China. Especially the huge Chinese geographical characters [5] push up the regional thermal design for indoor thermal comfort.

Hot summer and cold winter zone (HSCW) is a unique climatic zone [6] with great potential of discomfort in summer and winter. Local government has provided related building design standard for energy efficiency issues and healthy housing technical essential code. They set up lots of requirements on civil buildings within construction materials, thermal design parameters, building shape coefficient for reduction of thermal exchange, etc. Some related research [7-12] have linked the thermal performance with energy efficiency issues.

(D1-3)INVESTIGATION OF THE THERMAL COMFORT THEORY EXTENSION IN CHINESE LOW-ENERGY DWELLINGS IN HOT SUMMER AND COLD WINTER ZONE

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Abstract:

With the rapid development of the Chinese economy, more and more new generation residential buildings have been constructed for the Chinese housing market with low-energy approaches.The paper will discuss the thermal comfort theory and its possible extension to Chinese low-energy dwellings within Hot Summer and Cold Winter (HSCW) zone. It also surveyed the potential discomfort settings in existing residential buildings in China, particularly in HSCW zone, and a balance between indoor thermal comfort and energy saving. In the study, a typical prototype of Chinese high-rise apartment is investigated and simulated in DesignBuilder. Two different construction materials are set up in the computer model. The results of two different scenarios are revealed in the paper, also using the linear regression analysis between air temperature radiant temperature, operative temperature, outside dry-bulb temperature and 'Predicted Mean Vote' (PMV). The discomfort of overheating is also displaying the significant of adaptive comfort in low-energy building in specifically HSCW zone of China. Furthermore, related technical essential of innovations are carried out on the layout design, building fabric intervention and indoor human activity for adaptive thermal comfort.

Keywords:thermal comfort, low-energy dwelling apartment, building simulation, HSCW zone

1 Introduction

As the result of Chinese dwelling upgrade, more and more energy is used with the increased internal heat gains. However, the increasing energy shortage is leading a worldwide energy saving issues and the sustainable building design (low-energy building design) were legislated in the building environment code or design standard of each country. In China, energy saving target of 50% reduction in new buildings compared with the level in the duration between 1980-1981 has been clearly targetted in the last national development strategy of the 11th 'Five-year Plan' (2005-2010). Moreover, a higher aim of energy saving is established for the detailed discussion in the 12th 'Five-year Plan' (2011-2015).

The thermal comfort theoretical research starts from lab-based research. Thermal comfort is defined by 'ASHRAE Standard 55-92' [1] as a 'condition of mind that expresses satisfaction with the thermal environment'. The Fanger's class work [2] of thermal sensation is based on a large number of observing people in laboratory experiments, and then the PMV-PPD method was established for the related thermal comfort standards such as ISO 7730 [3] and ASHRAE Standard 55-92. However, in the field survey study [4-9], and the difference of the thermal evaluations has been debated for a long time with PMV, AMV and aPMV[10] of thermal model. Indoor overheating could happen by various occupants' thermal expectation and individual discrepancy of thermal tolerance. The adaptive approach pushed up the upgrade of ASHRAE Standard 55 to ANSI/ASHRAE 55-2004.

To summaries, the dwelling thermal comfort is not an independent research which should be combined with energy efficiency issues and the contribution of the research are aiming to trace the balance of comfort indoor thermal environment with low energy consumption. All the drives mentioned above pushed the research of low-energy dwellings unhesitatingly to go forward and the motivation are listed below:

(D1-4) A NEW APPROACH FOR ENERGY EFFICIENCY IN CHINESE APARTMENTS

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ABSTRACT:

In Chinese cities, residential buildings are typically high-rise or multi-storey. There is however some common problems such as overheating and heat losses within neighbouring units, especially with inefficient use of the heating energy generated from Chinese style daily cooking. According to literature, a high-rise apartment combines similar or different units on the horizontal plane, and the plane design could affect the interior thermal environment. In this paper, a comparison study of simulation work has been carried out using different typical apartments on selected horizontal planes again using an ‘entire building-scale energy saving’ concept, to promote energy efficiency technologies. The research deals with two issues: (1) The summary of thermal coefficients was extracted from local legislation and regulation, which is based on a typical unit of common Chinese apartments located in hot summer and cold winter zone. (2) DesignBuilder software package was used for simulation work of heating balance of internal gains and fabric heat performance. The findings in the study have shown that both the regional thermal coefficients and occupancy activities affect the energy use, and the fabric gains and thermal performance are directly related to the overall energy consumption, despite the apartment layout; horizontal or vertical. Chinese kitchen is considered an overheating area within housing space and there appears to be potentials for energy efficiency.

Keywords: Chinese apartments, sharing energy, cooking-energy efficiency, sustainable energy technologies,DesignBuilder

1. INTRODUCTION

In China, residential energy consumption dominates the total state energy use, particularly in post-occupied housing for providing cooling or heating for maintaining a comfortable indoor thermal environment to withstand the harsh climate effect. Generally speaking, the residential building is defined as the prototype of high-rise or multi-storey apartment in China.

1.1 Review of Energy Issues

According to 2009 Annual Report on Chinese Building Energy Efficiency [1] in China the entire energy consumption of the building industry accounts for 20% to 30% of total commercial energy consumption and about 20% of building energy is used during the raw material manufacture and building process, which means that the majority of building energy use occurred in post-occupied property maintenance [1]. According to nationwide statistics [2] energy efficiency and the unique characters of the regional climate situations [3] are key factors, which along with Chinese government target for 50% reduction of energy consumption of 1980 [3].

1.2 Status of Chinese Apartments

Chinese residential perception of ‘home’ stands for a physical shelter for defending against harsh outdoor climate situations.Figure 1 represent the appearance of contemporary residential building in a metropolitan city of China. Apartment is a common living style that isconstitutedof multi-household in one single residential building. Alongside Chinese development of infrastructure investment, various sources of social funding have beendirected to Chinese

(D1-5) URBANISM, MIXTURE OF SUSTAINABILITY, TECHNOLOGY, AND CULTURE: CASE OF OFF-GRID CITY, SOUTH KOREA, 2009

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Abstract:

Urban, architectural and technological design include several solutions in terms of energy efficiency and waste management as well as original cultural values of location, and contemporary requirements of high-tech 21st century life-style.

This article represents a ‘Zero Carbon, Zero Energy and Zero Waste’ attitude in different urban space with various functions such as Residential, Industrial, Business Commercial, Research, Cultural and Shopping spaces.

Moreover, it contains a background knowledge discussing sustainability, technological design, and local culture (i.e. values, traditions, and local high-tech artifices) investigating their roles as three major aspects of Urbanism and Architecture in a case study of design work (Off-Grid City 2009, Korea). Thus, it introduces the project as a combination of these three aspects.

Keyword:

Urbanism, Ubiquitous City, Environment-friendly city, Communal city, Off-grid city

1. Introduction

As the increasing population of human being in the world a new challenge has begun and more and more energy shortage, society classification and urban space organization start to redefine our urban development. In this situation, urban and building design brings along the need of further consideration of sustainability, technology and local culture values. In this article, thinking with investigation of how these three aspects can be presented together in a case study as a new urban vision and idea.

In March 2009, Inchon Urban Development Corporation (IUDC), South Korea held an international urban design competition. This competition aimed to contribute the transformation of Inchon Metropolitan City into a world-class city which is capable of carrying out commensurate functions and roles follows its future status and furthermore to reconsider the current urban issues for the city.