Adaptive Thermal Comfort in Residential Buildings, A Case Study of Wuhan

XIONG, Yan

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Professor Ho, Puay-peng (Chair)
Professor Tsou, Jin-yeu (Thesis Supervisor)
Professor Chan, Ying-keung (Committee Member)

ABSTRACT

As an innovative approach to achieve energy conservation and sustainable building development, studies of adaptive thermal comfort have been widely recognized in the recent years. Contextual variations in the living environments shape the diversity of occupants' adaptive thermal comfort and therefore more in-depth localized investigations are required, and this is true of current China. During the rapid urbanization process, many uncertainties still exist around residents' adaptive thermal comfort in terms of its adaptation process and underlying adaptively comfortable thermal boundaries which will contribute to housing energy conservation. This study addresses the above problems through investigation in residential buildings using the case of Wuhan, a typical city in the Hot-Summer and Cold-Winter climatic zone of China.

Field surveys and associated statistical analysis were employed as the main research methods for this study. The survey investigated 428 urban households to characterize their daily thermal behaviours and thermal requirements through questionnaires. Meanwhile, 513 sets of thermal comfort data draw from 71 households (in naturally ventilated buildings) reported residents' real thermal perception corresponding Hot-Summer and Cold-Winter climate. Longitudinal investigation on several families also was conducted to further explain some relevant non-climatic impacts.

This study reveals that local residents autonomously adapt themselves well to the local climate though all kinds of convenient and simple adjustments, such as dressing-habits, control of windows and doors, food and drink intake, intermittent and local heating/cooling pattern, and lower thermal expectation. In the naturally ventilated residential buildings, the measured indoor thermal environments were very hot-humid in summer and cold-damp in

winter, and were highly associated with outdoor climate. Occupants reported general acceptance and comfort in those conditions but would have preferred to be cooler in summer and warmer in winter. Meanwhile, based on the whole-year data, local residents' thermal perception including thermal sensation, thermal comfort, thermal preference and thermal acceptability, changes remarkably with the physical thermal variations; while this change rate is much lower in the respective seasons, so demonstrating the identified thermal adaptation. Longitudinal case studies indicate non-thermal factors including housing characteristics, consumer-values and living habits influence residents' adaptive thermal comfort significantly in addition to the climatic impacts.

Based on the comparisons between this study's results and others' previous work, for the residential buildings under local climatic conditions, the author suggests that adaptive model is represented as " Tn=0.6*Tout+9.8 " and the associated acceptable operative temperature range is from14℃ to 27℃ with the approximate relative humidity range of "10%~87%". The limitations and potential improvements of the conventional thermal indices "PMV-PPD" and "SET" when they are employed to predict adaptive thermal comfort are also discussed. Finally, the study suggests that "adaptive thermal comfort" should be encouraged as the thermal environment design goal rather than "static thermal comfort" in the China urban housing context.

The significance of this study is to provide an implementable adaptation model and acceptable temperature and humidity range for the residential buildings under local climate conditions, and to provide a broader database for general adaptive thermal comfort studies in terms of its adaptation process, extension of existing thermal indices for adaptive thermal comfort and adaptive opportunities creation in buildings.

伴随着全球对可持续发展及建筑能耗的关注，建筑环境中的“适应性热舒适”研究为建筑节能提供新的途径并逐步得到发展。“适应性热舒适”表现为建筑使用者对真实热环境的适应能力，气候差异及居民长期生活习性的不同决定了适应性热舒适的多样性，故其相关研究十分强调忠于“真实建筑环境”的调查。正经历着快速城市化阶段的中国城市住宅，面对人口基数大、建设量大、地区气候差异显著、人均建筑能耗低的现状及可预见的巨大住宅耗能需求，针对居民的适应性热舒适研究显得尤为重要且急迫。本论文选取夏热冬冷气候区典型城市武汉为研究案例，通过对当地居住建筑室内热环境及居民适应性热舒适的实地调研，确定该气候特征下居民可接受的舒适温度及湿度范围，并修正已有的热适应性模型以指导并规范住宅建筑的节能工作。

本研究对当地428户家庭进行了关于适应性热舒适的问卷调查以了解他们与居住热环境相关的行为特征；并在冬夏两季典型气候条件下通过对71户城市家庭实地测量、观察及访谈的方法取得513份有效热舒适问卷数据（自然通风状况下），且针对9户代表性家庭进行了深入的跟踪调查。在实地调研资料的基础上，本研究借助统计分析工具寻找适宜该地区居住建筑的适应性热舒适范围及热适应性模型。

实地调研结果表明自然通风状况下，居民家中普遍夏季闷热冬季湿冷，当地居民从衣着、降温取暖设备的使用习惯、对冷（热）环境的行为调节方式等都遵循着便利、有效的原则，并适当降低对某些家居活动的热舒适期待，从而获得整体上的适应性热舒适。从全年的气候变化看，居民对热环境的感知（包括热感觉、热舒适、热偏好和热接受）因物理热环境的变化而显著变化，但在单一季节里居民对物理热环境的感知相对迟钝，呈现明显的热适应性。通过对个别家庭的深入调查发现除基本气候因素外，住宅特征、消费观念及生活习惯等非气候因素同样影响着居民的热适应性。

在综合比较现有相关研究成果与本研究结果的基础上，本文建议适宜于夏热冬冷气候区（武汉）的适应性热舒适操作温度范围为14℃至27℃（相对湿度范围约为10%-87%），热舒适的适应性模型为“Tn=0.6*Tout+9.8”；且指出传统“PMV-PPD”及“SET”模型在自然通风住宅中解释适应性热舒适的局限性及其改进的可能性，并提出“适应性热舒适”应取代“中性热舒适”成为中国目前城市背景下住宅热环境设计的指导原则，推行更为健康和节能的居住模式。

此研究的意义一方面在于针对特定的气候类型（夏热冬冷地区）和居住环境（中国城市住宅环境下）深入了解当地居民的热行为特征并提出能有效指导热环境设计的适应性热舒适范围及适应性模型，另一方面则扩展了适应性热舒适研究的基础资料（尤其是在湿冷气候条件）有助于深入解适应性热舒适的作用机制。

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CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Protecting from a severe outdoor climate and providing comfortable thermal environments for occupants is one of the primary functions of building. For achieving this purpose, more and more energy has been consumed by the heating, ventilation and air-conditioning system in modern buildings since the advent of air-conditioning technology in 1890. Over 15% energy in US in 2006 (Arens, Humphreys et al. 2010), approximately 14% of household greenhouse gas emission in Australian (Wilkenfeld and LTD 2004), and more than 60% of building energy consumption in China is used for heating and cooling (Building Energy Research Centre 2008). In the context of sustainable building development in response to global climate change, the thermal comfort research communities started to rethink the relationships between the building itself, its system, and human thermal comfort needs in a revolutionary way, which provokes studies of adaptive thermal comfort that differ from conventional static thermal comfort models.

The new trend of adaptive thermal comfort study with the consideration of both comfort requirements and sustainable development has been widely recognized throughout the world in recent years (Oseland, Humphreys et al. 1994; Brager and de Dear 2001; Nicol and Humphreys 2002; Feriadi, Wong et al. 2003; van der Linden, Boerstra et al. 2006; Henze, Pfafferott et al. 2007; Pfafferott, Herkel et al. 2007; Jendritzky and de Dear 2009; Toftum, Andersen et al. 2009). However, there are still many uncertainties surrounding adaptive thermal comfort because of variations of climate conditions, building characteristics as well as individual variations between people.

Especially in current urban China, little work has been done to investigate what kind of thermal environment is comfortable for occupants in residential buildings, addressing adaptation; how occupants achieve their thermal comfort through all kinds of adjustments; and what kind of building and urban design strategies could be beneficial to adaptive thermal comfort acquisition instead of full dependence on an air conditioner. All these factors are crucial for the proper building thermal comfort standards establishment contributing to building energy conservation.

Unfortunately, a huge gap exists between existing building thermal comfort standards and real thermal requirements of residents in current urban China. On one hand, the government and designers are still using old thermal comfort standards without considering occupants' adaptation; on the other hand, residents have been acclimatized to their local climate and have adopted a lot of adjustments to achieve adaptive thermal comfort in the everyday life for so many years. The confliction means that huge unnecessary amounts of energy could be consumed in the near future if we do not profoundly understand human adaptive thermal comfort under this rapid urbanization process in China.

This study tries to address the above problems through in-depth investigation of local residents' adaptive thermal comfort in Wuhan under Hot-Summer and Cold-Winter (HS&CW) climatic conditions. As one city that is following a normal pattern of development, Wuhan is a very representative city for this study, not only for its typical climatic characteristics in the HS&CW climatic zone, but also for the presentation of the local residents' daily life style corresponding to their thermal environments.

1.2 Research Objectives

The primary objective of this research is to investigate and elaborate the thermal adaptation process in residential buildings. In a case study of Wuhan, under China urban housing environments, the following five specific objectives direct this research:

- To characterize local residents' thermal behaviours corresponding to the hot-humid and cold-damp climatic conditions in their daily lives;
- To exam local residents' thermal perception using a variety of thermal scales and thermal indices;
- To ascertain the acceptable temperature and humidity ranges for occupants in residential buildings in Wuhan, addressing adaptation;
- To develop an adaptation model in the local climate context and compare it to the existing thermal models;
- To explore the contextual and non-thermal impacts on adaptive thermal comfort.

1.3 Research Methodology

Field studies in the local residents' living environments and associated statistical processing are employed as main research methods in this study. The primary feature of this research method is the comparison of subjective thermal responses from occupants with corresponding objective thermal observations. This kind of research method has been examined by the international research communities in the field of adaptive thermal comfort study (de Dear, Brager et al. 1997; Humphreys, Nicol et al. 2007).

1.3.1 Field studies

There are three reasons for the adoption of fieldwork methods in this research. First of all, field study can provide the maximum authenticity of residents' thermal adaptation processes in their real living environments. Thermal adaptation is a dynamic process between human body and thermal environment. This kind of diverse condition is hard to design in fully controlled experiments, and the field study is a feasible method to investigate complicated human behaviors interacting with external environments. Secondly, the outside stimuli on occupants' thermal perception are more natural in the field studies compared with experiments, as well as the occupants' responses. Generally speaking, if the investigating conditions are more similar to reality, the research results would make a more usefully practical contribution (Yang, Wen et al. 2006). The purpose of studying adaptive thermal comfort is to further understand the human thermal perception mechanism and guide more sustainable design strategies in real living environments, and therefore results with more practical contribution are required by this kind of research. Thirdly, field study is very helpful to explore the objective phenomena as well as the underlying state of mind. The working process of adaptive thermal comfort has not been fully understood yet (Humphreys, Nicol et al. 2007), and we therefore need further exploration of the thermal adaptation process, and hope more potential motivations and other aspects could be clarified, based on field studies in real residential environments.

1.3.2 Statistical processing

Statistics is adopted as main data analysis tool for this adaptive thermal comfort study. Just as McCall points out: "*the major tasks of statistical analysis are to quantify the variability in a set of measurements; to describe the data for a group of subjects, despite the variability* *inherent in it, and to derive precisely stated and consistent decisions about the results by quantifying the uncertainty by variability*" (McCall, Kagan et al. 1986).

Descriptive statistical techniques are very useful to describe the characteristics of studied units. For this study, the investigation of adaptive thermal comfort pays close attention to housing characteristics, occupants' thermal behaviours in their daily life, subjective thermal perceptions, and objective indoor and outdoor thermal stimulus. The employment of descriptive statistical techniques is very helpful to display these studied variables' central tendency, variation or dispersion, positions and locations. Additionally, some inferential statistical techniques, such as regression techniques, also will be employed to quantify the relation within the studied units, such as the dependence of subjective thermal perceptions on objective thermal stimulus.

1.3.3 Research framework

The whole research framework for this adaptive thermal comfort study is displayed in Figure 1-1. Three columns show the progressive research process: data acquisition, data analysis, results interpretation and possible implementation. Each horizontal series shows the intrinsic logic of data input and potential outputs. Firstly, through the investigation of subjective thermal perception corresponding to indoor and outdoor thermal conditions, acceptable thermal range and thermal neutrality addressing adaptation could be found, and an adaptation model also could be drawn to establish a more realistic thermal comfort standard. Secondly, based on the collected information about indoor thermal condition and occupants' behaviours, conventional thermal indices can be calculated and therefore adaptive PMV/SET probably can be devised to fit occupants' subjective thermal perception and evaluate real thermal environments. Thirdly, the investigation of personal non-climatic variation and housing characteristics is helpful to define the adaptive opportunities contributing local residents' adaptive thermal comfort and promote more sustainable housing design strategies. More detailed explanation about research methods will be displayed in the Chapter 3 of Research Methods.

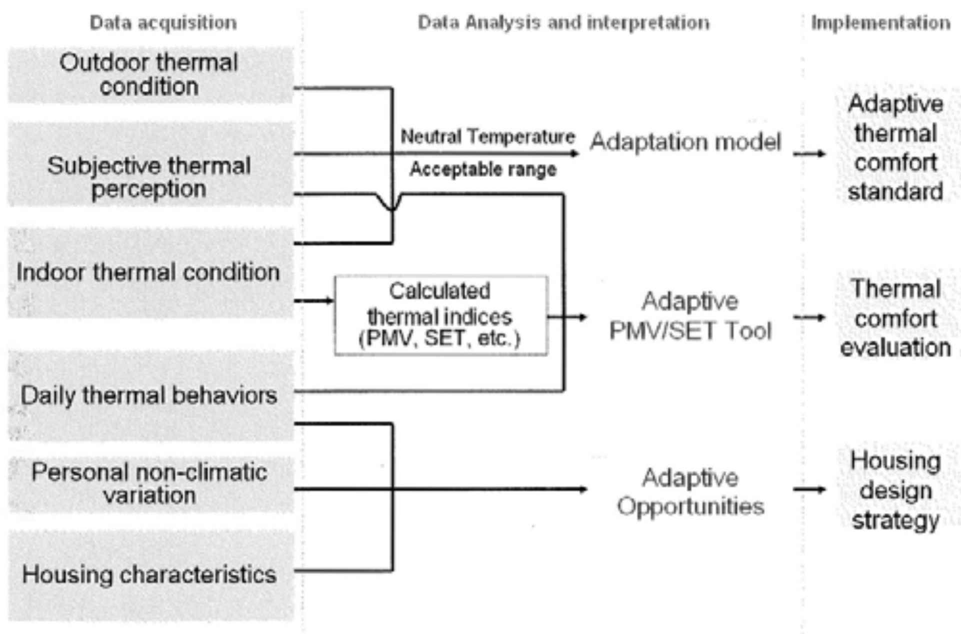

Figure 1-1: Research framework

1.4 SIGNIFICANCE OF RESEARCH

The long-term significance of this research is to promote more sustainable housing environments without compromising occupants' thermal comfort in a way that will help to tackle the global warming issue and future energy crisis. The findings of this research probably could help in the following ways:

- It suggests the comfortable temperature and humidity ranges in the residential buildings addressing thermal adaptation in Wuhan and cities within HS&CW zone. This extended range is useful to form a new thermal standard for local residential building design.

- It provides further understanding of the working process of adaptive thermal comfort which will be beneficial to designers and users. Occupants can obtain more specific knowledge to make personal and environmental adjustments to achieve thermal comfort and energy conservation without sacrificing their quality of live; meanwhile, architects and engineers can produce better design strategies and standards to match with occupants' adaptive desires for thermal comfort acquisition in the studied climatic zone.

Finally, all these research methods and results in Wuhan in the HS&CW zone can serve as useful information for other climatic zones and countries in terms of adaptive thermal comfort studies and housing design.

1.5 LIMITATIONS OF THIS STUDY

This study adopts field study and associated statistics as main research methods; some limitations should be stated clearly at the outset.

First of all, the underlying assumption is that people are able to act as 'meters' of their thermal environments when regression is performed of the comfort perception votes on corresponding thermal environments (Adebamowo 2007). The occupant is used as a comfort meter of all the environmental and personal variables simultaneously. However, there is the possibility that thermal comfort relates more closely to some more complex time-series of the environment, or some other non-climatic impacts, which are not usually taken into account in regression analyses.

Secondly, the regression analysis assumes that comfort perception votes are taken as the dependent variable and the environmental stimulus as the independent variables. However, during the adaptation process, occupants are freely left to adjust themselves through their choice of clothing, environmental controls, posture, and activity, etc... Actually, many of these actions will have been taken in response to the comfort vote within a behavioural feedback loop (de Dear, Brager et al. 1997). Therefore, the environments are not fully independent of the comfort votes. Meanwhile, usually the results found are specific to the conditions investigated, which means that generalization of any results from the statistical process must be treated carefully (Adebamowo 2007).

Thirdly, field study is both labour-intensive and prone to experimental error. Humphreys & Nicol also discussed the measurement and formulation errors in the adaptive thermal comfort research (Humphreys and Nicol 2000). Additionally, there is obviously a data shortage during the nighttimes and in the bedrooms for reasons of security and accessibility to respondents' homes (Adebamowo 2007). Apart from the errors from research methods, people's subjective responses may not be accurately expressed, leading to errors in thermal perception because of language interpretation and subjective misunderstanding, which means the thermal perception votes of each respondent probably are not numerically equally spaced for the statistical analysis.

Nevertheless, the research communities have acknowledged field studies and associated statistical analysis are useful ways to help us understand adaptive thermal comfort. Although these methods have been criticized by laboratory workers for their imprecision, the scientist must face the other way: "*the results of the field survey are facts that need to be explained, it is no answer to say that what they do cannot be true because they conflict with our theory*" (Adebamowo 2007).

1.6 Organization of the Thesis

This thesis is organized into six chapters.

Chapter 1 is introduction.

Chapter 2 gives a brief literature review of thermal comfort study and the developments of adaptive thermal comfort over the last forty years. The interactions between housing, thermal environment and occupant are also recalled in this chapter as well as previous studies done in China focusing on adaptive thermal comfort.

Chapter 3 presents research methods employed in this study. General climate and housing conditions of the studied city are introduced, and then research framework and implementation methods are presented, including the investigation's design, data composition, sample selection, measuring instruments, questionnaire development, investigation protocol, in-depth case study and statistical treatments of the collected data.

Chapter 4 reports the survey results of the field studies. Descriptive measurements of investigated households and individuals, residents' thermal behaviours and physical thermal environments measurements are presented. Quantitative comparisons between subjective thermal perceptions with objective thermal observation are conducted, in this chapter and investigation results from in-depth cases are also presented.

Chapter 5 discusses the research objectives based on the results from the field studies and comparisons with previous work. Challenges to conventional thermal indices' and what is the feasible thermal environment goal in the China urban housing contexts are also involved.

Chapter 6 concludes the research findings of this study and figures out the research limitations and gives directions for further work.

CHAPTER 2

LITERATURE REVIEW OF ADAPTIVE THERMAL COMFORT IN THE BUILDING ENVIRONMENTS

In ancient times before there were buildings, our ancestors knew how to live in a cave-home in winter and a nest-home in summer.

Book of Rites · Liyun

“昔者先王未有宫室，冬则居营窟，夏则居橧巢”。

---- 《礼记·礼运》

The maintenance of livable and comfortable environment for occupants is one of the primary requirements of housing. Even before the artificial building period, our ancestors knew how to protect themselves from naturally severe climatic conditions. Human beings can survive in greatly varied climates from North Pole to Equator. The success is attributable, not only to the fantastic climate-responding buildings, but also to the human adaptability to the thermal environments (Moran 1982).

In this chapter, a brief literature review about adaptive thermal comfort in building environments will be summarized into four parts. The first one is the conceptual basis of thermal comfort, and mainly introduces the conventional thermal comfort studies from the engineering perspective and the key idea of thermal equilibrium between the human body and ambient environment. The second part presents the recent developments of adaptive thermal comfort studies, including the theoretical understanding of adaptive thermal comfort and the empirical experiences from field investigation. The third part reviews the interactions between housing, occupants and thermal environments in urban China, and look at the climatic conditions, building setting and corresponding human behaviors from the multi-discipline view of architecture, environmental psychology and behavioral psychology. The last part is a review of previous work done in China focusing on adaptive thermal comfort in the building environments.

2.1 CONCEPTS OF THERMAL COMFORT

2.1.1 Thermal comfort and heat balance

Thermal comfort is defined by the ASHRAE Standard as "*that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation*" (ASHRAE 2010). The term of "comfort" is taken to describe "*a feeling of contentment, a sense of coziness, or a state of physical and mental well-being*" (Shove 2003). The research interest about thermal comfort concerns what kind of thermal conditions will be thought comfortable, which basic elements will affect this kind of comfortable thermal condition, and how we can evaluate a certain thermal condition as comfortable or not.

Because maintaining indoor thermal comfort is usually implemented through mechanical ventilation and heating/cooling systems in the industrialized society, this engineering perspective tends to determine that "thermal comfort" is one stable and precise condition. In 1970, Fanger established thermal equilibrium accompanying with skin temperature and evaporation rate requirements those assured thermal comfort. The key idea is that, within skin temperature and evaporation rate limits, thermal comfort will happen as internal heat production equal to heat loss to external environment. This equilibrium could be written as Equation (2-1)[1] and the detailed equation explanation is given in Appendix G.

$$H\text{-}Ed\text{-}Esw\text{-}Ere\text{-}L=K=R+C \qquad (2\text{-}1)$$

H: the internal heat production in human body;

E_d: the heat loss by water vapour diffusion through the skin

E_{sw}: the heat loss by evaporation of sweat from the surface of the skin;

E_{re}: the latent respiration heat loss;

L: the dry respiration heat loss;

K: the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing);

R: the heat loss by radiation from the outer surface of the clothed body;

C: the heat loss by convection from the outer surface of clothed body

To simplify the thermal equilibrium and its application, Fanger figures out six basic parameters affecting the thermal balance between human body and environments. They are air temperature (TA), mean radiation temperature (TM), air velocity (Op't Veld), relative temperature (RH), metabolic rate (MET) and clothing insulation (CLO) (Fanger 1970). In functional notation these six basic parameters can be represented as following equation (2-2), which means within the skin temperature and sweat rate limits human will feel thermally comfortable if the thermal load of his body equals to zero.

$$f(TA, TM, VEL, RH, MET, CLO)=0 \qquad (2\text{-}2)$$

[1] Fanger, P. O. (1970). Thermal Comfort: Analysis and Applications in Environmental Engineering. New York, McGraw-Hill Book Company: P22-42

2.1.2 Thermal sensation, predicted mean vote and predicted percentage of discomfort

Thermal sensation is a kind of subjective evaluation of a thermal stimulus. Bedford commented in 1954 "*the only way to find out how a man feels is to ask him, and the only sound way to establish comfort zones is by the careful questioning of large numbers of people*" (Auliciems 1972). A psycho-physical seven-point scale is often used to express occupants' feelings in responding to the thermal environment as "*cold, cool, slightly cool, neutral, slightly warm, warm, and hot*" shown in Table 2-1 (ASHRAE 2010). Also there are some other similar thermal sensation scales which are listed in this table. The major target of thermal environment design is to create one thermal condition in which most occupants can have a neutral thermal sensation. Then, how can we evaluate whether a certain thermal environment is comfortable or not? The Predicted Mean Vote (PMV) model is the most prevalent tool used all around the world nowadays and was developed by Fanger (Fanger 1970).

Table2- 1: ASHRAE thermal sensation scale, Bedford scale and other sensation scales[2]

Bedford scale (Bedford 1936)	ASHRAE55 & ISO7730	Modified ASHRAE scale (Humphreys and Nicol 2004)
+3 much too warm	+3 hot	+3 much too warm
+2 too warm	+2 warm	+2 too warm
+1 comfortable warm	+1 slightly warm	+1 slight too warm
0 comfortable	0 neutral	0 Just right
-1 comfortable cool	-1 slight cool	-1 slightly too cool
-2 too cool	-2 cool	-2 too cool
-3 much too cool	-3 cold	-3 much too cool
Comfortable perception	Thermal sensation	Change the center category to the optimum unambiguously

[2] Feriadi, H., Wong, N. H., Chandra, S., & Cheong, K. W. (2003). Adaptive behavior and thermal comfort in Singapore's naturally ventilated housing. Building Research & Information, 31(1), 12-22.

The reason of advocating PMV tool is that the heat balance equilibrium (Equation (2-1)) is too complicated for laypersons. Based on the principle of "neutral means heat balance", Fanger constructed the PMV model to evaluate particular thermal conditions. The model indeed calculates the thermal load of human body and predicts subject's vote of thermal sensation. The equation can be derived as Equation (2-3)[3] and detailed equation explanation is given in Appendix G.

$$PMV = (0.352e^{0.042(M/Adu)} + 0.032)Load \qquad (2\text{-}3)$$

This equation states that the PMV is a function of thermal load of occupant. If the "load" equals to zero, then the PMV value will be zero representing a neutral thermal sensation. If it were easy to measure the six basic thermal parameters of thermal equilibrium, it would not be difficult to calculate the thermal load of the subject under one certain condition and therefore PMV tool can evaluate this kind of thermal condition.

At present, the most widely used thermal comfort standards, such as ASHRAE 55:2010 (*Thermal Environmental Conditions for Human Occupancy, Atlanta GA, American Society of Heating Refrigeration and Air-condition Engineers*) and ISO 7730:2006 (*Ergonomics of the thermal environment-Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*) both adopt the PMV model as their basic thermal environment evaluation tool.

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[3] Fanger, P. O. (1970). Thermal Comfort: Analysis and Applications in Environmental Engineering. New York, McGraw-Hill Book Company: P114

2.1.3 Different viewpoints about thermal comfort and thermal sensation

Based on the definitions of thermal comfort and thermal sensation, there are three viewpoints discussing the similarity and differences of these two terms (Zhao 2000).

Viewpoint (1): Thermal comfort equals to neutral thermal sensation, which is supported by Houghton, Yaglou, Gagge & Fanger. It means an occupant will feel thermal comfortable if his thermal sensation is neutral. Under this condition, humidity and air velocity should be in a certain range and is the occupant must be in a stable condition.

Viewpoint (2): Thermal comfort does not equal to neutral thermal sensation, which is supported by Ebbecke, Hensel & Cabanac. They thought comfort meant satisfaction and happiness controlled by the combined stimulation of different sensory receptors of body, while the thermal sensation is controlled only by thermal stimulus under skin sensory receptors. Thermal comfort only exists under dynamic conditions.

Viewpoint (3): Thermal comfort and thermal sensation are different, while thermal comfort can exist under both stable and dynamic conditions. Thermal comfort is more subjective compared with thermal sensation. Under stable conditions, thermal comfort is consistent with neutral thermal sensation, while under dynamic conditions; thermal comfort maybe is not consistent with the neutral thermal sensation (Zhao 2000). Thermal comfort is a more dynamic term through which occupants express subjective conscious feeling.

These controversial discussions focusing on thermal comfort and thermal sensation display that thermal comfort is, rather than thermoreception and temperature regulation, a varied individual response and more broad. Social-cultural contexts also could influence occupants' comfort perception. In other words, the thermal comfort in artificially stable environments could be different from that in the naturally dynamic environments.

2.1.4 Neutral temperature, preferred temperature and acceptable temperature

Although thermal comfort is determined by six basic parameters from the engineering perspective of heat equilibrium, temperature is still the most obvious and understandable parameter among them, and temperature is the simplest indicator to control an HVAC system from the view of practice. Usually, scientists like to establish psychometric charts to show comfortable temperature ranges combining temperature with other parameters, such as Figure 2-1 which indicates the dynamic relationship between thermal comfort boundary with operative temperature and humidity (ASHRAE 2010).

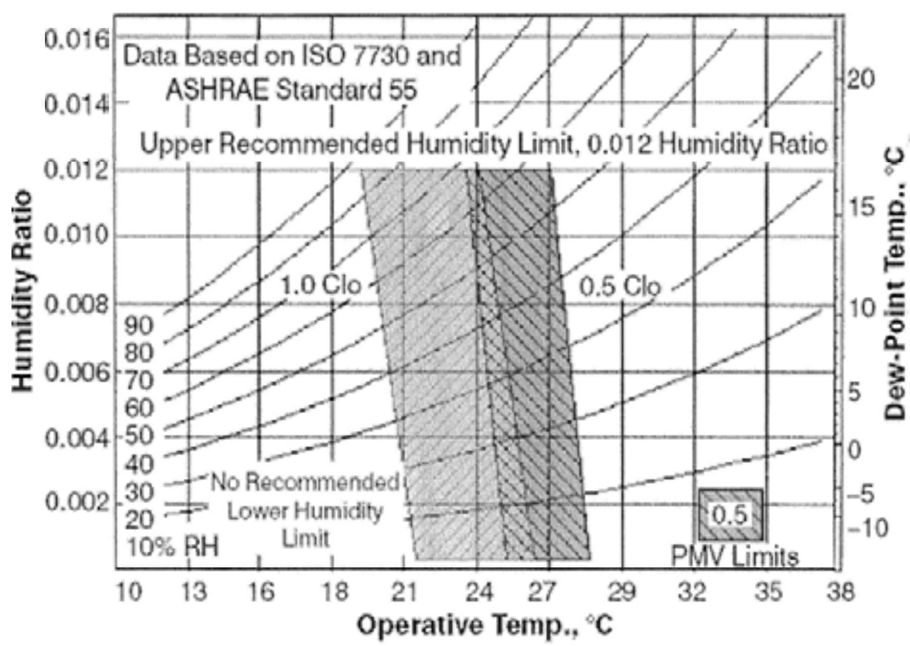

Figure2- 1 Acceptable range of operative temperature and humidity for spaces[4]

Oseland and Humphreys summarize that there are three common research methods to

[4] ASHRAE (2004). ASHRAE Standard 55:Thermal Environmental Conditions for Human Occupancy. Atlanta, ASHRAE: P5

find the comfortable temperature (Oseland, Humphreys et al. 1994). One is to investigate several people at same time and calculate the comfortable temperature by regression analysis of their thermal sensation votes. This method actually measures the neutral temperature corresponding to "0" thermal sensation vote. Another common method was developed by Fanger through setting up a climate chamber, adjusting temperature according to the wishes of the occupants by asking whether they would prefer it warmer or cooler. This method indeed measures occupants' preferred temperature. The third method is to ask people "do you find the current thermal environment acceptable". This method actually measures acceptable temperature voted by occupants.

Neutral temperature is the calculated comfortable temperature for the majority of occupants, and it is widely used in the thermal comfort research especially in the field survey. In other words, the most "comfortable temperature" drawn from field surveys actually is a "neutral temperature" found by regression analysis.

Preferred temperature is a kind of psychological need for thermal environment. The most prominent discrepancy of preferred temperature and neutral temperature possibly comes from perceiving and preferring. This means people in hot climate may prefer a sensation slightly cooler than neutral, while people in cold climate prefer a slightly warmer one (Humphreys 1975). This mechanism was also illuminated by Yao Runming, using black-box theory of automation (Yao 1997).

Acceptable temperature is also a dynamic temperature for comfort, and consequently quite different thermal environments may be accepted in different circumstances (Oseland, Humphreys et al. 1994). Sometimes an acceptable temperature is far from the neutral temperature. Nervertheless, acceptability is probably the ultimate aim of building design and it has big potential for building energy conservation (Oseland, Humphreys et al. 1994).

All these three kinds of temperature normally are located in the zone of vasomotor and vasodilator regulation and possibly all of them can make occupants feel comfortable. What temperature do we need to adopt for building thermal environment design? This question has aroused interest in the research of thermal adaptation because of the discrepancy that is possible between neutral temperature, preferred temperature and acceptable temperature. Humphreys explained some reasons of this discrepancy from internal (human) and external (environment) angle and suggested that neutral point defined by ASHRAE is not necessarily the optimum for thermal comfort (Humphreys and Nicol 2004; Humphreys and Hancock 2007; Humphreys, Nicol et al. 2007).

2.1.5 Thermal indices

As people know more about the complexity of thermal comfort, many single thermal scales are proposed to describe the combination of major factors of temperature, humidity, air movement and radiation affecting thermal comfort (Bedford 1936; Yaglou and Minard 1957; Olggay 1963; Fanger 1970; Gagge, Stolwijk et al. 1971; Gagge and Nishi 1976; Gagge, Fobelets et al. 1986). These single thermal scales do simplify the implication of thermal comfort in the building environments in terms of thermal environment evaluation and occupants' thermal comfort prediction. Some indices used most frequently are listed as follows.

Operative temperature (TOP) (Winslow, Gagge et al. 1939)

Operative temperature was developed by Winslow, Herrington and Gagge in USA. It combines the effects of air temperature and radiation temperature with omission of humidity and air movement. Operative temperature is defined as "*uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by* *radiation plus convection as in the actual nonuniform environments*" (ASHRAE 2010). As an index comprising air temperature and radiation temperature, operative temperature is widely used in the psychometric chart for thermal comfort study.

Predicted Mean Vote/ Predicted Percentage of Dissatisfaction (PMV/PPD) (Fanger 1970)

PMV/PPD has been the most popular index used in the fields of thermal comfort until now. The meaning of "PMV" has been illustrated in the Section 2.1.2. The international definition of "PMV" is that "*an index that predicts the mean value of the votes of a large group of person on the seven-point thermal sensation scale*", and "PPD" is "*an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV*" (ASHRAE 2010). Therefore, PMV and PPD actually is a single evaluation tool, but expressed in two ways. The ideal thermal environment should assure PMV value in the range of "-0.5~0.5" where only 10% occupants feel dissatisfied, and acceptable thermal environment have a PMV value in the range of "-0.85~0.85" where less 20% occupants feel dissatisfied.

Effective Temperature (ET^*) (Gagge, Stolwijk et al. 1971)

"*ET^* is probably the most common environmental index, and has the widest range of application. It combines temperature and humidity into a single index, so two environments with the same ET^* should evoke the same thermal response even though they have different temperatures and humidities, as long as they have the same air velocities.*"(ASHRAE 2005) Effective temperature was originally developed in 1923~1925 at the research laboratory of ASHVE by Houghten, Yaglou and Miller (Givoni 1976), and Gagge et al. defined the new effective temperature (ET^*) through rational approach as the temperature of an environment at

50% relative humidity that results in the same total heat loss from the skin as in the actual environment (Gagge, Stolwijk et al. 1971).

Standard Effective Temperature (SET) (Gagge, Fobelets et al. 1986)

On the basis of Effective Temperature (ET^*), more meaningful and comparable index of Standard Effective temperature is developed. It is the equivalent dry bulb temperature of an isothermal environment at 50% relative humidity in which a subject, with standard clothing (0.6clo) and standard activity (1met), would have the same heat stress (skin temperature) and thermal regulatory strain (skin wettedness) as in the actual test environment (Gagge, Fobelets et al. 1986). The SET scale adds in the subjective impacts on respondents of their clothing insulation and metabolic rate, therefore it should be more reliable to predict thermal comfort comparing ET and get widely used in building thermal environments.

2.2 Adaptive Thermal Comfort Developments

The research of adaptive thermal comfort tries to understand the human being's thermal comfort in a more realistic way through field studies in everyday conditions. Since the publication of Bedford's study in 1936, many researchers began to put their interests into occupants' thermal perception and thermal requirements in real building environments instead of controlled thermal chambers (Humphreys, Nicol et al. 2007).

Basically, the development of adaptive thermal comfort research can be summarized into three parts here: theoretical understanding of adaptive thermal comfort, research methods for thermal adaptation and empirical investigation of adaptive thermal comfort in the field.

2.2.1 Theoretical understanding of adaptive thermal comfort

The research interest in adaptive thermal comfort was invoked in 1970's and people have started to become concerned about the huge energy consumption for maintaining conventional thermal comfort in the building environments. Actually, the recognition process of "comfort" reveals the shifting history of social normality (Shove 2003) .

"*Comfort*", from the Latin verb "*confortare*", was originally defined as a spiritual factor with the meaning of mental or physical strength, encouragement or consolation (Shove 2003). Thermal comfort also was defined as a mental satisfaction with thermal environment (ASHRAE 2010). With the development of modern society, thermal comfort got more emphasis on the relationship between human's body and ambient physical environments, and this kind of transformation coupled with the modernization process. In the last century, the invention of air-conditioning technology made the precise controlled comfort-environment to be taken for granted by society, and comfort became an attribute of environment design. Air-conditioning culture has started to spread widely around the world during this industrialization and globalization process.

Nevertheless, in recent years, with the consideration of climate change and sustainable development, thermal comfort has been put on to the desk again and people find human beings can achieve thermal comfort through so many approaches. Comfort becomes an "achievement" instead of an "attribution" of environment design (Shove 2003). The intrinsic interaction of the human being and the corresponding environment shows that a static physical condition is not necessary, and human beings knows how to adapt to broad thermal environments through all kind of adjustments, and finally "adaptive thermal comfort" got recognition (Humphreys, Nicol et al. 2007).

2.2.1.1 The definition of thermal adaptation in the building environments

The adaptive principle was defined by Humphreys as: "*If a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort*"[5]. de Dear also pointed out that a person was not a passive receptor of sense-impressions, but a dynamic and active agent responding to the thermal environment and "*accounts for the ways in which a person's past experience, future plans, and intentions influence one's perception*" (de Dear, Brager et al. 1997). There are all kinds of actions that can be taken to modify the rate of internal heat generation, the rate of body heat loss, the thermal environment or selecting a different thermal environment (Humphreys 1997). The conceptual thermal adaptation mechanism can be drawn and displayed as the Figure 2-2 (Brager and de Dear 1998).

"*Adapt comes from Latin adaptare, meaning to adjust. The original meaning of adaptation is therefore adjustments*" (Helson 1964). In terms of adjustment objects, human being can adjust themselves to become comfortable in the prevailing conditions (roughly left side of the Figure 2-2), and also can adjust the surrounding environments to meet subjects' requirements (roughly right side of Figure 2-2) (Humphreys and Nicol 2004). The former one is determined by the internal adaptive mechanism of human body which can be called internal adaptation. The latter one is affected by the external mechanism of the interaction of human body and thermal environment, and can be called external adaptation. Through external adaptation, people's behavioural adjustments help them maintain thermal comfort to the greatest extent (de Dear, Brager et al. 1997).

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[5] Humphreys, M. A. (1997). An adaptive approach to thermal comfort criteria. Naturally ventilated buildings. D. Clements-Croome. London, E & FN Spon: P130.

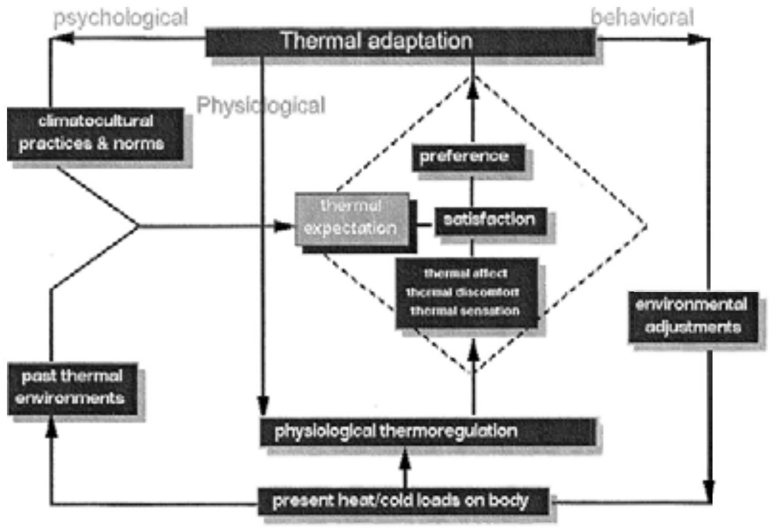

Figure2- 2: The thermal adaptation mechanism[6]

The adjustments go into effect in four time scales. Cutaneous thermoreceptors provide almost instantaneous neural information about sudden changes in the thermal environment, such as crossing the indoor/outdoor threshold will spring the clothing adjustment instantaneously (Brager and de Dear 1998). A longer time scale is that of adopting some behaviours, such as using fans, catching natural ventilation, operating curtains or blinds, etc., can consequently change physical thermal environments and improve occupants' thermal sensation logically (Brager and de Dear 1998). The much bigger time scale is some living habits and custom formed through long life responding certain living conditions and cultural impacts, such as siestas, bathing, sleeping outdoors and taking a walk after sunset for outdoor activity avoiding burning sun. The biggest time scale is developed through genetic heritage beyond several decades or more, such as acclimatization of Inuit in the arctic cold (Moran 1982).

[6] Developed by Auliciems, 1981 and modified by de Dear and Brager, 1998, P7

The impacts of adaptation acting on thermal sensation is fundamentally determined by adaptive opportunities which refer to whether or not buildings (context) afford occupants scope for adaptive intervention (Baker and Standeven 1994). More adaptive opportunities mean more potential to compensate discomfort (Brager and de Dear 2000). In naturally ventilated buildings with controllable windows, no strict constraint about clothing and personal behaviours, thermal adaptation is more evident than air-conditioned or HVAC buildings. Generally, compared with other types of building, naturally ventilated homes have the most opportunities for thermal adaptation because of most freedom for adjusting environments and occupants themselves.

2.2.1.2 Thermal adaptation approaches

Thinking from the adaptation and operating approach, Brager classified adaptations into three categories: behavioural adjustment, physiological adjustment and psychological adjustment (Brager and de Dear 1998).

2.2.1.2.1 Behavioural adjustments: personal, environmental, technological, or cultural

Behavioural adjustment includes all modifications a person consciously, or unconsciously makes, which would modify heat and mass fluxes governing the body's thermal balance (Wohlwill 1975). Brager defined behavioural adjustments into three subcategories: (1) personal adjustment of adjusting the surroundings by personal changes; (2) technological or environmental adjustment and (3) cultural adjustments (Brager and de Dear 1998).

The personal adjustment may be related to some factors as follows: (a) personal demography, (b) personality, (c) economic condition, (d) desire for energy conservation, (e) physiological condition, (f) psychological expectation of thermal environment, (g) cultural regulation, (h) living habits and so on. The technological or environmental adjustment opportunities largely depend on contextual factors (Nicol and Humphreys 1973). De Dear and Brager indicated that these opportunities for behavioural adjustments mainly come from: (Ⅰ) an attribute of the building itself; (Ⅱ) characteristics of facilities, or heating/cooling systems in building (de Dear, Brager et al. 1997); (Ⅲ) cultural adjustments which are more relevant to organizational or social customs prevailing within the living environment, living habits, and so on.

Displayed in Figure 2-3, the feedback loop of behavioural adjustment illustrates that "*what might have previously been regarded as the final consequence in the static heat balance model (the conscious sensation of thermal discomfort), becomes the starting point for this feedback in the adaptive model*" (de Dear, Brager et al. 1997).

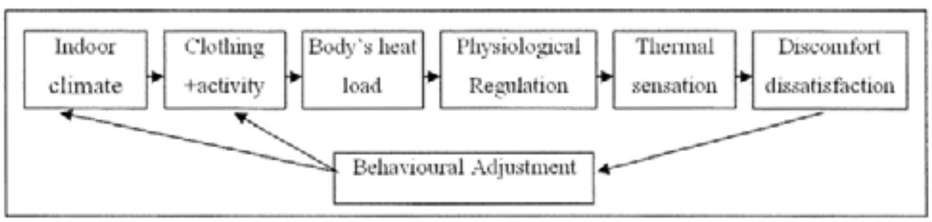

Figure2- 3: Behavioural feedback loop[7]

2.2.1.2.2 Physiological adjustments: genetic adaptation or acclimatization

Physiological adaptation also can be divided into at least two subcategories according time-scale: (1) genetic adaptation alterations which come from genetic heritage of an individual or group of people, developing through long time beyond that of an individual's lifetime, such as Eskimo and (2) acclimation or acclimatization changes in the settings of the physiological thermoregulation system over a period of days or weeks, such as immigration from north to

[7] de Dear, R., G. S. Brager, et al. (1997). Developing an adaptive model of thermal comfort and preference. Sydney & Berkeley, Macquarie Research Ltd., Macquarie University & Center for Environmental Design Research, University of California: P10

south or inverse (Brager and de Dear 1998). The realization of physiological adaptation is more time consuming comparing behavioural adjustments.

"*Physiological acclimatization is mediated by the autonomic nervous system and directly affects the physiological thermoregulation set points*" (Brager and de Dear 1998). The physiological adjustment is mainly related to human body itself, so it is an internal adaptation mechanism and more in-depth research work on these processes takes place in the subject of medicine or physiology. The heat balance models adopted in building environment do not recognize this form of adaptation, assuming these set points to be fixed.

2.2.1.2.3 Psychological adjustments: habituation and expectation

Psychological adaptation gives more attention to cultural impacts and people's cognitive process, which indicates that one's thermal perception and thermal reaction will change as his habituation and expectation to thermal environment changes (Brager and de Dear 1998). Fanger also extended his PMV model by adding an expectation value. This extended PMV model agrees well with field studies in naturally ventilated buildings and shows the existence of psychological impacts on thermal adaptation (Fanger and Toftum 2002).

It is not easy to release the psychological secret of the thermal adaptive processes. As a learning process, occupants become accustomed to their prevailing climate and will adopt a more suitable expectation for thermal environment because they live in this place for a long time and become familiar with the climate characteristics. However the scale of changing expectation does not only depend on outside factors, but also on the subject's own psychological structure which varies from one to another. So, how to predict occupant's psychological adjustment is still not well constructed.

2.2.1.2.4 Social and cultural impacts

After integration of above three adaptation approaches, considerable impacts coming from social and cultural background could be found. Shove named it a "co-evolution" process, which reveals the interaction of technology, practice and normality. In her opinion, thermal comfort can be achieved beyond the science of temperature, ventilation and humidity control, which means that it can be achieved through social and cultural stimulus and reinforcement (Shove 2003).

If the idea of social and cultural diversity could be recognized by the research communities of adaptive comfort, it is very sensible and reasonable to find the varied results from the field investigations in different nations and climate regions all around the world.

2.2.1.3 Research methods for thermal adaptation

2.2.1.3.1 Climate chamber—thermal balance

Climate chamber work is the most conventional research method for thermal comfort study, and therefore some researchers started to study thermal adaptation through this method. The advantage of climate chamber method is the feasibility of comprehensive measurements in controlled conditions and an experimental design based on the physiological thermal balance model. This method is ideally suited to testing adaptive feedbacks insofar as the thermal environment is artificially controlled. Climate chamber experiments done by Fanger showed acclimatization had little impact on occupants' preferred temperature; studies in Hong Kong and Singapore also failed to find adaptation in different regions, but A Abdulshukor's work done in Malaysia found 3℃ higher neutral temperature of person living in hot climate (Brager and de Dear 1998).

However, climate chamber also has its weakness for studying thermal adaptation. As an experimental strategy for thermal comfort, climate chamber method has higher internal validity to show impacts of all the variables on the sample's thermal perception, but lower external validity to generalize the research results to the population. Furthermore, because of the lack of realistic living situations in a climate chamber, researchers cannot find diverse thermal adaptation that is happening in the real building environments. As a more valid method reflecting real thermal conditions and real subjective thermal perception, the method of field study has been widely used by many researchers.

2.2.1.3.2 Field study—dynamic loop of subject and thermal environment

Unlike climatic chamber studies, field studies of thermal adaptation are conducted in people's real living conditions with more diversity and adaptive opportunities. It is the principal method to find the dynamic loop of people and their living habitats (Humphreys, Nicol et al. 2007).

Because the aims of field studies are to clarify working process of these adjustment opportunities and evaluate the effects of all these factors to human thermal comfort, two sorts of information must be carefully dealt with in fieldwork study. One is the objective thermal environment, and the other one is the subjective responses of occupants. The first sort of information comes from climate as well as building characteristics, such as various kinds of physical climatic data, space forms, electronic facilities and controllability of the environments. The second sort of information comes from the occupants, including their demographic data, their lifestyle, their thermal expectation, and expressed thermal perception corresponding to real thermal settings.

As Humphreys pointed out that field study "*...concerns the whole range of actions people take to ensure their comfort, the adaptive approach touches on many topics including climatology, the design and construction of buildings, the provision and use of thermal controls, the history and sociology of clothing and the influence of culture, together with* *human thermal physiology. It therefore encompasses all those aspects of thermal comfort studied in the laboratory*" (Humphreys, Nicol et al. 2007). The method of field study brings its advantage of revealing more realistic comfort levels in real living environments, but also brings the complexity and difficulty of explaining this dynamic process.

2.2.1.3.3 Statistical analysis of data

Facing lots of data from climate chamber or fieldwork, researchers need suitable methods to analyze them. Statistics, as one quantitative analysis tool, is one important and commonly-used method for analysis of thermal comfort and thermal adaptation. As for the thermal adaptation, statistical techniques are employed to check the impacts on thermal comfort of different climatic parameters, environment controllability, occupant's expectation, etc. Meta-analysis was employed firstly by Humphreys to deal with worldwide field data thirty years ago (Humphreys 1975), and the research communities have widely used statistics as one key method to organize and summarize information from field surveys, to generalize questionnaire's answers from obtained sample, and quantify research results for practical application.

Generally, regression modelling is widely employed to quantify the relation between subjective thermal perception and corresponding thermal environments. So many regression models have been produced by the worldwide researchers (Mallick 1996; de Dear, Brager et al. 1997; McCartney and Fergus Nicol 2002; Feriadi, Wong et al. 2003; Olesen and Brager 2004; Schweiker and Shukuya 2009), which will be discussed in the Section2.2.2 of empirical investigation.

2.2.1.4 Adaptation model

Although we can illustrate thermal adaptation theoretically from several different aspects, from the view of practical application, a mathematic expression of adaptation processes, the so-called adaptation model, is still needed in the research communities.

Adaptation model is "*a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters*" (ASHRAE 2010). The most common representation of this model is simple linear regression model from Equation (2-4) [8] and graphed in Figure 2-4, which indicate that indoor comfortable temperature depends on outdoor temperature. The detailed equation explanation is given in Appendix G.

$$Tc = a*Tout+b \tag{2-4}$$

Tc: comfortable temperature
Tout: outdoor temperature
a, b: coefficient and constant

[8] Three papers discuss the detailed determination the outdoor temperature as follows:
Nicol, F. and M. Humphreys "Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251." Building and Environment 45(1): P11-17
Nicol, F. and M. Humphreys (2007). "Maximum temperatures in European office building to avoid heat discomfort." Solar Energy 81: P298
van der Linden, A. C., A. C. Boerstra, et al. (2006). "Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate." Energy and Buildings 38(1): P12

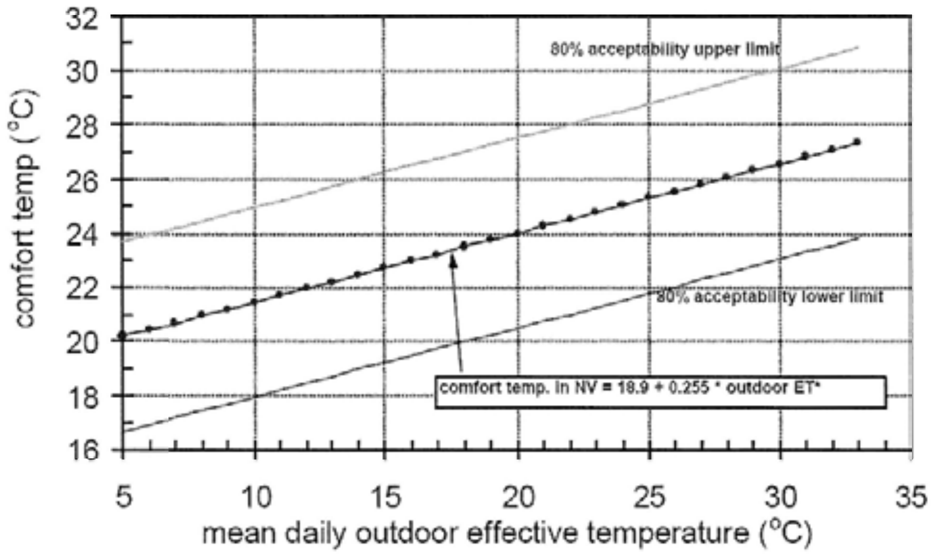

Figure2- 4: Linear regression model of thermal adaptation[9]

Most previous research work about adaptive thermal comfort was to find an appropriate thermal adaptation model for a certain area, such as one city, one country or one similar climatic region. The broadest work was conducted by ASHRAE and covered four continents and a broad spectrum of climatic zones. This kind of adaptation model can establish the correlation between comfortable indoor temperature and prevailing outdoor temperature, as in ASHARE Standard 55-2010. It incorporates the adjustment of clothing as part of the adaptive process.

Another form of adaptation model is the extended PMV model for non-air-conditioned buildings in warm climates by adding an expectation value. It can be expressed as Equation (2-5)10 and the detailed equation explanation is in Appendix G.

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[9] de Dear, R., G. S. Brager, et al. (1997). Developing an adaptive model of thermal comfort and preference. Sydney & Berkeley, Macquarie Research Ltd., Macquarie University & Center for Environmental Design Research, University of California: P169

10 Fanger, P. O. and J. Toftum (2002). "Extension of the PMV model to non-air-conditioned buildings in warm climates." Energy and Buildings 34(6): P534

$$PMV_{new}=e*M_{adjusted}PMV_{old} \qquad (2\text{-}5)$$

Alongside simple linear regression predicting comfortable indoor temperature and extended PMV model, another approach of thermal adaptation modelling is about the prediction of adaptive behaviours. It uses logistic regression analysis to calculate the probability of behavioural adjustments and explores its application in thermal simulation (Nicol, Rijal et al. 2007). The relationship between the objective thermal environment and various kinds of behavioural controls in naturally ventilated buildings, such as opening windows, using fan, using curtain, using heater, etc.., can be shown through stochastic regression analysis. This kind of prediction can help to get more accuracy in building energy simulation (Nicol and Humphreys 2004). The representative form can be written as following Equation (2-6) [11]and plotted as Figure 2-5.

$$Log\ (p/1-p) = a*T+b \qquad (2\text{-}6)$$

p: probability that one kind of behaviour is adopted
T: indoor or outdoor temperature
a, b: coefficient and constant

[11] Nicol, F., H. Rijal, et al. (2007). Characterising the use of windows in thermal simulation. 2nd PALENC Conference and 28th AIVC Conference, Heliotopos Conferences: P714

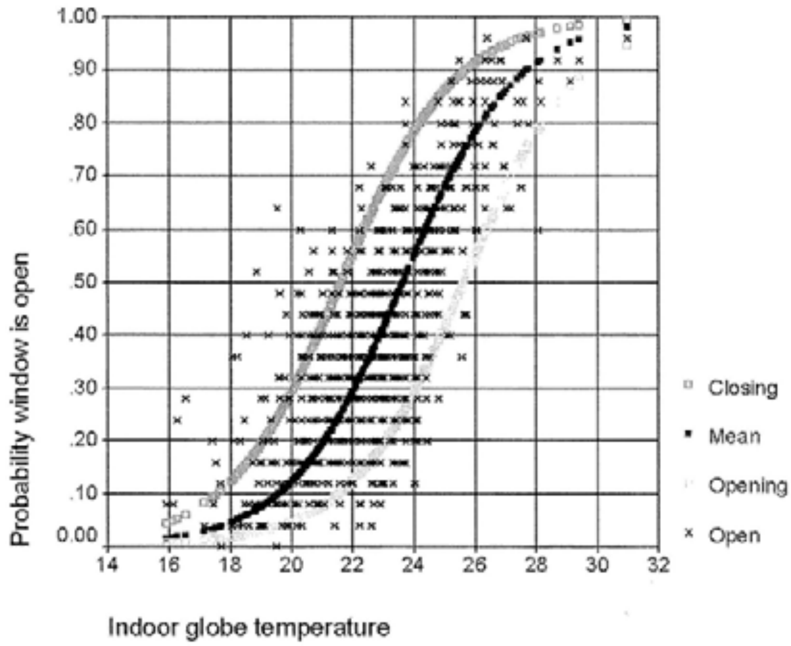

Figure2- 5: Logistic model of probability of certain adaptive behaviour[12]

2.2.2 Empirical investigation of adaptive thermal comfort

The recent revisions of ASHRAE Standard 55-2010 and EN 15251-2007 have adopted the thermal adaptation mechanism in naturally ventilated buildings. The ASHRAE Standard is based on the database of the RP-884 project led by ASHRAE in 1997, Standard EN 15251 uses data from the European SCATs project led by Oxford Brookes University in 2001 (de Dear, Brager et al. 1997; Nicol and Humphreys 2009).

All these published results focusing on adaptive thermal comfort can be categorized into two types: one is prediction of neutral temperature and the other one is prediction of adaptive behaviours. These predictions show a relationship between neutral temperature and

[12] Nicol, F., H. Rijal, et al. (2007). Characterising the use of windows in thermal simulation. 2nd PALENC Conference and 28th AIVC Conference, Heliotopos Conferences: P713

mean outdoor temperature; a relationship between thermal sensation and indoor operative temperature, an estimation of neutral indoor temperature or a preferred temperature. Table 2-2 displays some adaptation models studied in different regions (Humphreys 1978; Auliciems 1981; de Dear, Brager et al. 1997; Humphreys and Nicol 1998; Nicol, Raja et al. 1999; McCartney and Fergus Nicol 2002; van der Linden, Boerstra et al. 2006; Nicol and Humphreys 2007); Table 2-3 presents the real thermal sensation's dependence on operative temperature, and the neutral operative temperature perceived by occupants (Schiller, Arens et al. 1988; Donnini, Molina et al. 1996; Mallick 1996; de Dear, Brager et al. 1997; Karyono 2000; Cena and de Dear 2001; Feriadi, Wong et al. 2003; Brager, Paliaga et al. 2004; Ida, Francesco et al. 2004); Table 2-4 also displays more neutral temperature findings from tropic area (Feriadi, Wong et al. 2003).

Table2- 2: Some adaptation models draw from different field studies around the world

Researchers	Survey Location	Year	Regression models (℃)
van der Linden, A. C. Boerstra, A. C. Raue, A. K. Kurvers, S. R. de Dear, R. J.	----	2006	90% Acceptance Te,ref > 12℃, Top<20.3+0.31Te,ref Te,ref < 12℃, Top<22.7+0.11Te,ref
			80% Acceptance Te,ref > 11℃, Top<21.3+0.31Te,ref Te,ref < 11℃, Top<23.45+0.11Te,reff
			65% Acceptance Te,ref > 10℃, Top<22.0+0.31Te,ref Te,ref < 10℃, Top<23.95+0.11Te,reff Te,ref: The reference outdoor temperature; Top: Indoor operative temperature
Auliciems, Andris	----	1981	Tn=0.314Tout +17.6 Tn=9.22+0.48Ti+0.14Tm Ti: the mean air, globe or operative temperature Tm: the mean monthly temperature outdoors(average of mean daily minimum and maximum)
de Dear, Richard Brager,Gail Schiller Donna, Cooper	countries in 4 continents	1998	Tn=0.255Tout +18.9 (ET)
Humphreys, Michael A.	----	1978	Tn=0.534Tout+12.9 Tn= 0.534Tout+13.2

	----	1998	Tn= 0.546Tout+13.5(adjusted)	
Nicol, Fergus	Pakistan	1999	Tn=0.36Tout +18.5	
	SCATs database	2007	Tcomf=0.33Trm+18.8	
McCartney, Kathryn J. Nicol, Fergus	France	2002	T_{MR80}<=10℃ T_{MR80}: running mean temperature	T_{MR80}>10℃
			0.049T_{MR80} +22.58	0.206T_{MR80} +21.42
	Greece		----	0.205T_{MR80} +21.69
	Portugal		0.381T_{MR80} +18.12	0.281T_{MR80} +18.12
	Sweden		0.051T_{MR80} +22.93	0.051T_{MR80} +22.83
	UK		0.104T_{MR80} +22.58	0.168T_{MR80} +21.63
	All		22.88℃	0.302T_{MR80} +19.39

Table2- 3: Some findings of dependence of thermal sensation on indoor operative temperature

Researchers	Year	Location	Regression models	Neutral operative temperature (℃)	Correlation coefficient
Brager	2004	San Francisco	TSV=0.19Top-4.20 (winter) TSV=0.30Top-6.9 (summer)	Winter: 22.1 Summer: 23.0	R=0.69 R=0.90
Cena K & de Dear	2001	Hot and arid climate	TSV=0.21To-4.28(w) TSV=0.27To-6.29(s)	Winter: 20.3 Summer: 23.3	R=0.8426 R=0.8888
de Dear	1997	NV buildings	TSV=0.27Top-6.65	24.63	
Donnini G, et al	1996	Cold climate	TSV=0.493To-11.69	Winter: 22.6 Summer: 24.1	R=0.9899
Feriadi	2003	Singapore	TSV=0.34ET*-9.98	29.35(ET) Acceptable ET: 25.1~28 Preferred ET:25.1	R=0.3363
Ida	2004	Bari	TSV=0.28Top-5.821	20.79	R=0.872
Karyono	2000	Jakarta	TSV=0.31Top-8.33	26.87	R=0.648
Mallick	1996	Dhaka	TSV=0.18Top-5.11	28.39	R=0.500
Schiller GE	1988		TSV=0.26ET*-5.83	Winter:22.0 summer:22.6	R=0.9274

Notes: TSV- Thermal Sensation Vote

Table2- 4: Some research findings of neutral temperature in tropic area

Researchers	Year	Location	Building type	Research findings (℃)
de Dear (residential)	1991	Singapore	NV	Neutral tem=28.5(TOP)
Busch (office)	1992	Thailand(Bangkok)	NV	Neutral tem=27.4(ET) Upper bound of acceptable level=31(ET)
Henry Feriadi	2001	Singapore	NV	Neutral temp=29.3 (ET) or 28.6(TOP)
Karyono(office)	1998	Indonesia (Jakarta)	NV & AC	Neutral T for both AC+NV occupants=26.7(TOP)
Khedari et al (classroom)	1999	Thailand(Bangkok)	NV	Neutral temp=28 (Air temp) at 0.2m/s
Kwok (classroom)	1998	Hawaii	NV	Neutral temp=26.8 (ET)
Mallick (residential)	1996	Bangladesh (Dhaka)	NV	Neutral temp=28.4(Globe temp)
Sharma (residential)	1986	India (Roorkee)	NV	Specified comfortable at 28(TSI), Thermal sensation change interval of 4.5℃
Webb(residential)	1959	Singapore	NV	Comfort zone=25.94+-(0.42)

Notes: NV- naturally ventilated buildings; AC- air-conditioned buildings

In addition to prediction of temperature, some research results of behaviour prediction could be found. Nicol in UK observed that when the indoor temperature was higher than 20℃, the number opening of windows rises steeply with indoor temperature and approaches 100% at the temperatures above 27℃; when outdoor temperature was lower than 15℃ few people would open windows, while if it was over 25℃ and most windows were opened. The data also indicated that an indoor temperature of 20℃ and an outdoor temperature of 15℃ were the thresholds for switching on fans (Nicol and Humphreys 2004). A similar finding was drawn for Pakistan: opening windows and drawing blinds or curtains were used most frequently to release heat and block radiation; the usage proportion increased as indoor or outdoor instantaneous temperature increased; more fans were used in buildings with fewer open window; occupants with more controls reported less discomfort (Nicol, Raja et al. 1999).

In short, the greatly varied field results come from different nations and climatic regions cannot be fully explained by the thermal physiology alone. The cultural and social impacts should be taken account in achieving adaptive thermal comfort, as mentioned before.

The evidence from field studies tells us that adaptive thermal comfort research is context-based, and occupants' cultural background and living society should be mentioned in each study. As pointed out by Hitchings, thermal comfort study should take the path between "history evidence" and "field evidence" (Hitchings 2010). Therefore, for this study, the China urban housing environments also need to be figured out.

2.3 Housing, Thermal Environments and Occupants in Urban China

Since the Urban Housing Reform in 1998, China urban housing has achieved tremendous development, such as house ownership changes from public to private or semi-private, much higher house prices, much better house quality and more diverse housing prototypes. Based on data from Wuhan Statistical Bureau, in 1998, urban housing investments were 4.81 billions RMB but 33.0 billions RMB in 2007. Meanwhile, only 45% of real estate investment was put into housing projects and 3.35 million m^2 floor space of housing was completed in 1998. In 2007, 72% of real estate investment was put into housing and 8.12 million m^2 floor space of housing was completed[13] (Han and Wu 2004). The per capita living space also has increased from 8.1 m^2 to 28.3m^2 during the same period.

During this rapid development process, Chinese people wanted to shake off poverty and acquire better living quality as fast as possible. Achieving comfortable thermal environment in homes has raised vast domestic energy consumption in China because of its rigorous climate conditions and living quality requirements. The particulars of Chinese urban housing environments and residents' desire for comfort will be unfolded in the following sections.

[13] Data from Wuhan Statistical Bureau

2.3.1 Comfort desire and energy consumption

The strong desire for comfort has caused greater dependence on mechanical heating, cooling and ventilation system in building environments; consequently much energy has been consumed for maintaining indoor thermal comfort. Before the Economic Revolution, living quality in China did not get enough attention because of low productivity and unstable political situation. Along with the development of a Market Economy, people have started to spare no effort to improve their living quality. Data from Wuhan Statistical Bureau shows that from 1995 to 2007 air-conditioner ownership per 100 households increased from 26 to 150.6[14]. Meanwhile, 320 millions ton of Standard Carbon[15], more than 62% total building energy consumption, was used for cooling and heating in 2004 in China (Building Energy Research Centre 2008).

Although the total building energy consumption is huge in China, compared with other developed countries, Chinese per capita building energy consumption is much lower. As Figure 2-6 displayed, each Chinese urban resident each year only consumes one tenth of the energy an American consumed, and the average building energy consumption per square meter per year in China is approximately only one third of the average for developed countries. Jiang also pointed out that living-philosophy played an important role, influencing building energy consumption (Jiang 2007). In China, people prefer a relationship of harmony between building and nature rather than artificially controlled environments. As far as more specific energy consumption for maintaining thermal comfort, Table 2-5 also repeats that Chinese per capita cooling energy consumption in summer and heating energy consumption

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[14] Data source from: Wuhan Statistics Yearbook

http://www.whtj.gov.cn/Article/ShowClass.aspx?classid=440&classname=%E7%BB%9F%E8%AE%A1%E5%B9%B4%E9%89%B4

[15] 1Kg Standard Carbon=0.28KWh

in winter in the HS&CW climatic zone is much lower, compared with that of developed countries.

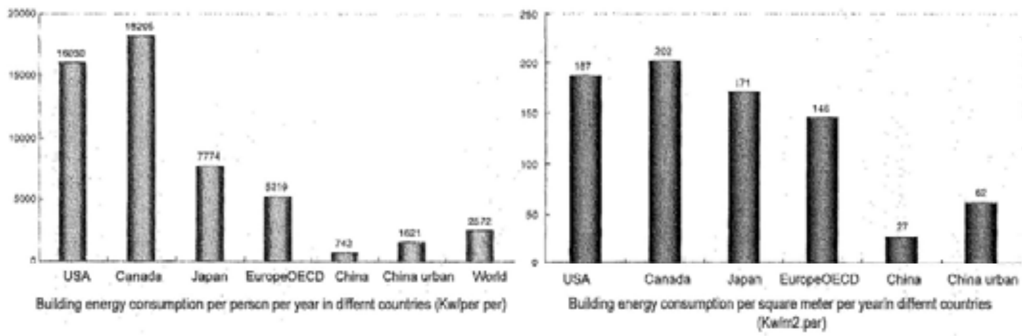

Figure2- 6: Comparison of building energy consumption between China and developed counties[16]

Table2- 5: Energy consumption in residential buildings for cooling or heating (kWh/m^2.year)[17]

US /Heating	US/ Cooling	German/ Heating	China Northern area with central heating	China HS & CW zone without central heating	China/ Cooling
70	12.5	145	90	4~8	2.7

On the whole, the Chinese current environment-friendly life-style results in lower per capita building energy consumption, but their strong comfort desire and huge population determines that huge energy demands would be a big challenge for the national development in the future.

[16] Jiang, Y. (2007). "Architecture energy saving and living pattern (建筑节能与生活模式）." Architecture Journal （建筑学报）(12). P12

[17] Data source: China & German: 2008 Annual Report on China Building Energy Efficiency. Beijing: China Architecture and Building Press. 2008. P16,P19;

US: Department of Energy. Building Energy Databook 2008. P2-5, P2-7

2.3.2 Occupants' role in building energy conservation

Building energy conservation has been widely initiated in response to the worldwide energy crisis and globe warming. Like other nations, China also is implementing many regulations to encourage more building energy conservation (GB/T 50378-2006, GB50176-93, GB50189-2005, GB50362-2005, JGJ134-2001, JGJ75-2003, JGJ26-95, JGJ129-2000, SJG10-2003, etc.). However, most of these regulations only examine the energy saving potential from the building aspects; what is the occupants' role in this national campaign? IPCC (Intergovernmental Panel on Climate Change) has said that the strategies for building energy conservation could be launched not only from the approaches of technology, policy, measurement and instruments, but also from the approach of occupants' behaviours and life-style (Table 2-6) (Barker, Bashmakov et al. 2007).

Table2- 6: Three approaches for building energy conservation[18]

Technologies	Policy, measurements and instruments	Behavior and life style
Efficient lighting and daylighting; More efficient electrical appliances and heating and cooling devices; Improved cook stove; Improved insulation; Passive and active solar design for heating and cooling; Alternative refrigeration fluid; Recovery and recycling of fluorinated gas; Integrated design including intelligent control and feedback, solar photovoltaic	Appliance standards and labeling; Building codes and certification; Demand-side management programmes; Public sector leadership programmes, including procurement; Incentives for energy service companies; Tax or other economic encourage	Advocating proenvironment behaviors and life style: switch off lighting, appliances, heating or cooling devices before leaving; reducing unnecessary heating or cooling, employ high efficiency devices, etc

[18] The table is modified based on IPCC 2007 Report.

Source: Barker, T., I. Bashmakov, et al. (2007). Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch and L. A. M. R. Dave. Cambridge and New York, Cambridge University Press. P54, 57

In urban China, the culture of frugality, Mianzi (face) and the idea of going with the stream play an important role in stimulating those behaviours beneficial energy saving. On the basis of VBN theory (value-belief-norm), Stern summarized some causal factors of proenvironment behaviours, such as attitude, personal capabilities, contextual factors, habit and routine (Stern 2000). Because one traditional virtue, frugality, has dominated Chinese' consumption attitude and consumption behaviour for thousands years, people would prefer acceptable discomfort rather than perfect comfort, if it cost less. On the other side, "Mianzi (face)" also influences occupants' consumption behaviour. For example, the ownership of advanced air-conditioners and over-cooled space, in a sense, sometimes becomes a way of showing off social status and wealth rather than fulfilling real thermal requirements. Additionally, in terms of idea of going with the stream, Yates et al emphasized the importance of learning from neighbours, which can contribute to energy saving in residential buildings (Yates and Aronson 1983). In urban estates, friends, neighbours and colleagues like to discuss their purchasing intention, living experience and consuming style. This is one important channel for education and information aiming at pro-environment behaviours.

No matter how well a building is designed, its energy performance will in the end greatly depend on how the people are living in it, working in it and behaving in it, and to what extent they make use of energy efficiency provisions. Barker, Bashmakov et al also pointed out that "*because of the important role of non-technological opportunities in buildings, ambitious GHG reductions may require a cultural shift towards a society that embraces climate protection and sustainable development among its fundamental values, leading to social pressure for building construction and use with much reduced environmental footprints*" (Barker, Bashmakov et al. 2007). The better one understands the logic behind human behaviour, the more chance one has to succeed with technologies. However, the understanding of why individuals are behaving in a certain way in relation to indoor climate and purchase/use of energy efficient appliances is still limited, and the understanding of how to influence their behaviours in a positive way is even less well understood (UNEP 2007).

2.4 Previous Work Done in China Focusing on Adaptive Thermal Comfort

2.4.1 Empirical studies in China

Although most work on thermal adaptation, especially theoretical work, was conducted overseas, researchers did run some pilot work in different climatic regions of China. Through field studies in 66 residential buildings in Harbin and 120 sets questionnaires from local residents, Wang Zhaojun found the neutral temperature of residents living in Harbin in winter was 21.5℃; At the same time, females' neutral temperature was 1℃ higher than males'. She also pointed out that Chinese people living in northern area (Harbin, Beijing & Tianjin) were less sensitive to temperature variation than were people in Montreal and Townsville (Wang, Wang et al. 2003). Xia Yizai investigated 88 houses with natural ventilation and pointed out the neutral temperature is 25.3℃(Ta) and 26.7℃ (ET^*) in Beijing, while 80% residents can tolerate temperature as high as 30℃ (ET^*) in naturally ventilated buildings (Xia, Zhao et al. 1999). Additionally, Jian Yiwen and Jiang Yi found the thermal environments in Beijing residential building were far from a comfortable level. Improving roof and envelope insulation and ventilation in nighttime will make a great contribution for summer thermal environments in this area (Jian and Jiang 2002). Through investigation in summer in Shanghai, Shi Ruihua, Shi and Li found despite of indoor average temperature as 30.1℃ and average relative humidity as 64.9%, while outdoor average temperature as 32.3℃ and the average relative humidity as 65.8%, most residents felt satisfied with thermal conditions (Shi, Li et al. 2005). Li Baizhan's work showed that in Chongqing's classrooms in winter, low temperature and high relative humidity were the main reasons for thermal discomfort and the acceptable temperature was 14.04~24.2℃, and the observed thermal sensation was different from the calculated PMV (Li, Liu et al. 2007). Han, Jie et al. compared urban and rural residents' thermal comfort in naturally ventilated environments and suggested that rural occupants may have more tolerance to coldness than urban occupants because of their physiological acclimatization, or have relatively lower thermal expectation than urban occupants because of few air-conditioners used in the rural area (Han, Yang et al. 2009).

The published results focus on several cities, such as Shanghai (Li, Shi et al. 2005; Shi, Li et al. 2005; Ye 2005), Changsha (Ye 2005), Xian (Wang, Wang et al. 2003; Yoshino, Guan et al. 2004), Chongqing (Tang 2001; Tang, Xie et al. 2006), Beijing (Xia, Zhao et al. 1999; Yoshino, Guan et al. 2004), Tianjing(Zhu 2004), Harbin (Yoshino, Guan et al. 2004; Wang 2006), Dalian (Pen 2003). Among these cities, Shanghai, Chongqing, Xian and Changsha are all in the Hot-Summer and Cold-Winter climatic zone of China.

2.4.2 Thermal standards in Hot-Summer and Cold-Winter climatic zone

Currently, China is adopting ISO 7730-2005 as the national standard for indoor thermal environment design, which defines three categories of thermal environment fulfilling different PMV range of "-0.7~0.7", "-0.5~0.5" and "-0.2~0.2". For the specific HS&CW climatic zone, Design Standard for Energy Efficiency of Residential Building in Hot Summer and Cold Winter Zone (JGJ134-2001) is applied to guide regional building energy conservation (The Ministry of Construction 2001). With the consideration of energy consumption and economic development in the Hot-Summer and Cold-Winter climatic zone, Fu categorized desired indoor thermal environment into two categories which are shown in Table 2-7 (Fu 2002).

Thermal requirements of category B can be attained through passive design strategies and improved building thermal performance, while category A needs additional active heating/cooling system both in summer and winter.

The existing regional design standard (JCJ 134-2001) addresses category A as its design goal for comfortable indoor thermal environments. Additionally, for air-conditioned building, the desired indoor thermal condition is 26℃ in summer and 18℃ in winter with one air-change per hour ventilation rate, which is also widely used for all the building energy conservation calculation (The Ministry of Construction 2001).

Table2- 7: Indoor thermal environment categories for Hot-summer and Cold-winter climatic zone[19]

	Category A		Category B	
	Summer	Winter	Summer	Winter
PMV	≤0.57~0.76	≥-0.70~-0.40	≤1.45	≥-2.11
Dry bulb temperature (℃)	≤26~28	≥16~18	≤30	≥10
Unsatisfied ratio from field investigation (%)	0	≤5	≤30	≤91
PPD (%)	≤12~18	≤7~12	≤50	≤80

2.5 SUMMARY

It can be concluded from the above review that, as a new innovative developing trend responding to the need for energy conservation and sustainable building environments, adaptive thermal comfort research is still at an early stage in terms of both its theoretical basis and practical methodology. Probably because of the greatly varied climate and building conditions, worldwide investigations focusing on adaptive thermal comfort show broad diversity even when they share the same theories and research methods. Meanwhile, occupants themselves play an important role in the interaction between subjective thermal

[19] Fu, X. (2002). Technology for building energy conservation in Hot Summer and Cold Winter Zone（夏热冬冷地区建筑节能技术）. Beijing China Architecture and Building Press.

responses and the objective thermal environment. Especially in current urban China, residents' strong thermal desire and their well-adapted thermal behaviours show the need for more comprehensive study of localized adaptive thermal comfort. For the HS&CW climatic zone, the few pilot adaptive thermal comfort studies are not profound enough to characterize occupants' thermal behaviours and consequently to interpret this dynamic adaption process. More in-depth investigations that accept this double challenge are urgently required.

CHAPTER 3

RESEARCH METHODS

This chapter seeks suitable methods to study local residents' adaptive thermal comfort in the China urban housing environments. The theory and logic of these research methods and their implementation will be discussed. The chapter firstly describes the general information on local climate and urban housing conditions in Wuhan. Then it presents the research framework and methods of approaching data acquisition and data processing for this study. The investigation design, data composition, sample selection, measuring instruments, questionnaire development, investigation protocol, in-depth case study and statistical treatments will be unfolded step by step.

3.1 REGIONAL CONTEXT OF WUHAN

For this research's objectives, Wuhan is a very typical city in the HS&CW zone of China, not only because of its climatic characteristics, but also because of the life-styles led by the common residents in the urban housing environments. Unlike international cities such as Shanghai, Wuhan is a more traditional city, where residents can adopt all kinds of behavioural opportunities to adjust themselves and their environments to restore their comfort both in summer and winter. Research results derived from Wuhan would be quite representative of the HS&CW climate and of city residents, and therefore Wuhan probably can be considered typical of other cities in the same climatic conditions.

3.1.1 Wuhan's climatic environments

There are five main climatic zones in China. They are categorized for building thermal design according to average maximum temperature in summer and average minimum temperature in winter as shown in Figure 3-1. The HS&CW Zone is defined as climatic regions where coldest month's average temperature is between 0℃ and 10℃ and hottest month's average temperature is between 25℃ to 30℃ (The Ministry of Construction 1993). Generally, most area of this zone is located in the south of the Longhai Line, north of Nanling， and east of Sichuan basin. It covers two directly governed city region—Shanghai and Chongqing; five whole provinces—Hubei, Hunan, Jiangxi, Anhui, Zhejiang; the eastern part of Sichuan and Guizhou; the southern part of Jiangsu and Henan; the northern part of Fujian; the southern point of Shanxi and Gansu; the northern point of Guangdong and Guangxi. Totally, this climatic zone includes 16 provinces and 550 million people and covers 1.8 million square kilometres of land, with high population density and high economic development speed (The Ministry of Construction 2001). Wuhan, as a metropolis in the central China with latitude of 29°58′N ~31°22′N and longitude of 113°41′E~115°05′E, is fully within the HS&CW Zone of China.

Figure3- 1: Five main climatic zones for building design in China and the location of Wuhan[20]

In the HS&CW Zone, the most remarkable climatic feature is a "hot–humid" summer as well as a "cold-damp" winter, which is shown by Wuhan's standard weather data of temperature and humidity (Figure 3-2)[21]. This figure shows that, in the whole year, only very few hours fall into the conventionally comfortable thermal band (band 1) and the majority falls into either hot-humid zone or cold-damp zone. Another notable climatic feature of Wuhan is the four distinct seasons and relatively long summer and winter. Usually, spring starts from 18th March lasting 61days; summer starts from 18th May lasting 128 days; autumn starts from 23rd September lasting 56days; and winter starts from 18th November

[20] Figure translated from: The Ministry of Construction, P. R. C. (1993). Thermal design code for civil building（民用建筑热工设计规范）, China Planning Press.

[21] China Standard Weather Data (CSWD) source: National Meteorological Information Center, C. M. A. and T. U. Department of Building Science (2005). Special Meteorological Data for Building Thermal Environment Analysis in China. Beijing, China Architecture and Building Press.

The chart is drawn using Climate Consultant 3 software and each point in this chart represents one hour's climate data with dry-bulb temperature and humidity. Meanwhile, different design strategies are suggested to corresponding climate conditions.

lasting 120 days[22] (Fu 2002). Meanwhile, Wuhan's monthly temperature and humidity displayed in Figure 3-3[23] shows that, both in hot summer and cold winter, the relative humidity is quite high.

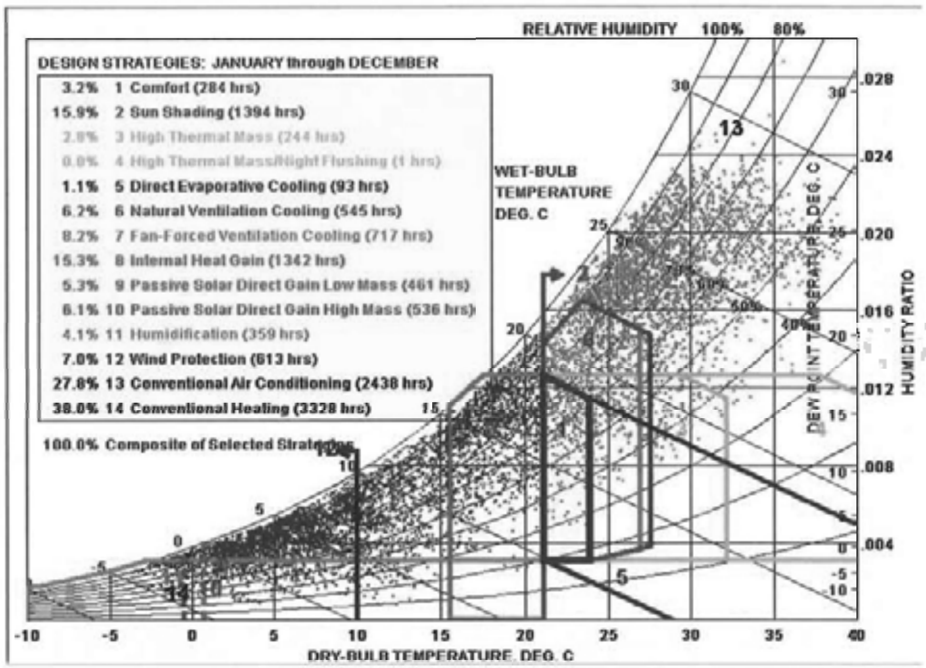

Figure3- 2: Psychometric chat of Wuhan in the whole year

[22] Definition of winter: uninterrupted five days with mean temperature lower than 5℃; definition of summer: uninterrupted five days with mean temperature higher than 22℃.

[23] China Standard Weather Data (CSWD) source

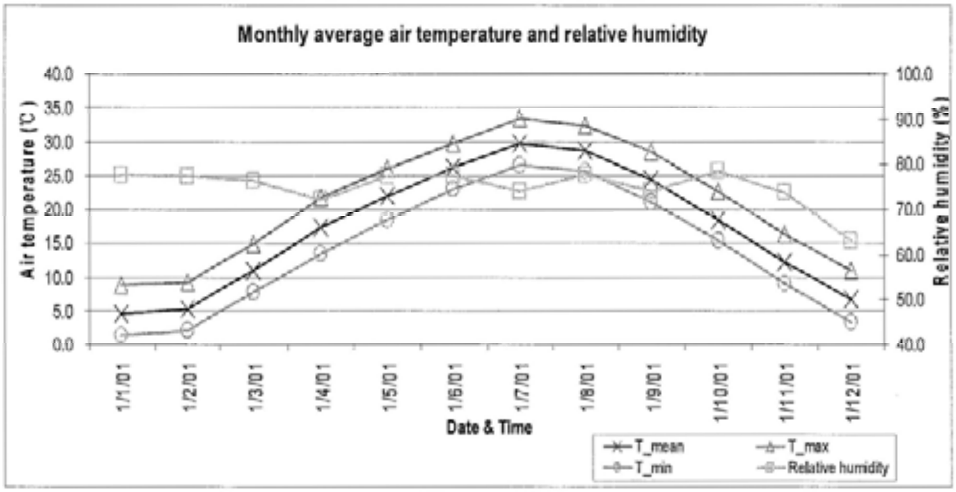

Figure3- 3: Wuhan's monthly temperature and relative humidity

In the HS&CW Zone, according to existing building design standards and regulations (GB50176-93 & JGJ134-2001), residential buildings are not required to be equipped with a central heating/cooling system (The Ministry of Construction 1993; The Ministry of Construction 2001). But the reality is that during most time of winter and summer, the thermal environments in residential building are reported uncomfortable by local residents[24] (Fu 2002) and some reasons for this kind of uncomfortable thermal environment in buildings also are discussed by Fu as follows (Fu 1998).

"In summer: (1) continuous radiation and high temperature generated by the pacific subtropical anticyclone over the Yangzi River from Shanghai to Sichuan province. In the daytime, city heats up gradually with increased air velocity, while at night, air outdoor temperature drops down accompanied by decreased air movement, and therefore the heat stored in the buildings cannot be taken away efficiently during night; (2) bad ventilation in buildings and (3) bad envelope insulation of buildings.

[24] In summer, occupants reported that during 87.5% time they felt uncomfortable and even could not maintain normal daily life during 36.5% time because of the hot weather.

In winter: (1) insufficient direct sunlight[25] and low air temperature; (2) bad building envelope design, such as bad thermal insulation and cold infiltration from windows and doors; and (3) the residents' habit of keeping a window open for fresh air even on very cold days[26]."

Under these climatic conditions, residents have to face a double challenge from the hot summer and the cold winter. As Moran wrote, human being had learned to adapt themselves to get more comfortable in this climatically varied natural environment over a long history, no matter whether around the equator or near the poles (Moran 1982). Under this particular climate of Wuhan, local residents also have to learn to achieve thermal comfort effectively for their survival and life.

3.1.2 Urban housing conditions in Wuhan

Adaptive thermal comfort is highly associated with local context and study-objectives (Hitchings 2009), which means that the urban housing environments in Wuhan must be presented before studying the local residents' adaptive thermal comfort.

3.1.2.1 Good nature resource: river, lake, mountain and park

The rich natural landscape resources in Wuhan, such as river, lake and mountain, supply a lot of open space beneficial to urban housing planning. The Yangzi River and Hanshui River divide the big city into three main districts: Wuchang, Hanyang and Hankou as displayed in Figure 3-4. The main lakes in the centre city, such as East Lake, Sha Lake, Yue Lake and South Lake, together with some nearby mountains, supply a lot of beautiful and comfortable

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[25]Direct sunlight ratio： Beijing67%, Shanghai43%, Wuhan39%, Changsha27%, Chengdu21%, Chongqing13%. Direct sunlight ration: the ratio of real hours with direct sunshine over the hours could get direct sunshine per month or per year

[26] Fu's survey results show that only 9% residents won't open the windows in winter.

outdoor open space to residents. Even in the city centre, which is very dense and crowded, most residents can release their thermal stress in this green open space, especially in the hot summer evenings.

The abundant green space supplies ample opportunities for local residents to compensate for their indoor thermal discomfort during severe weather, both physiologically and psychologically.

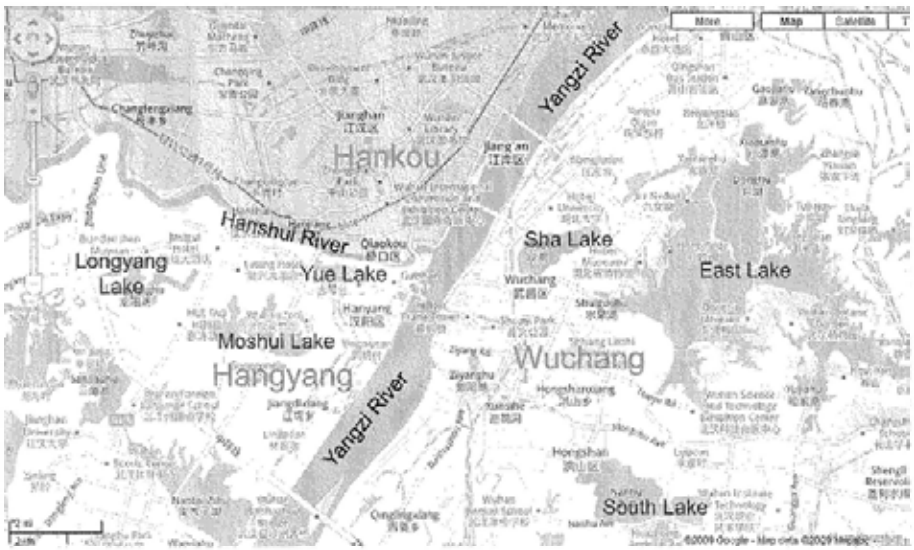

Figure3- 4: Rivers, lakes and mountains in the centre city [27]

3.1.2.2 Monotonous housing form and layout

Most of urban houses in Wuhan have very similar form and layout. The strict regulations on building distance for sunlight, and the uniform construction technology determine that most of residential buildings look very similar. They are linearly located along with Yangzi River or facing south and north, and 5 to 8 stories high without elevators (Figure 3-5, 3-6).

[27] Figure is modified from Google Map

Figure3- 5: Typical residential building layout in Wuhan[28]

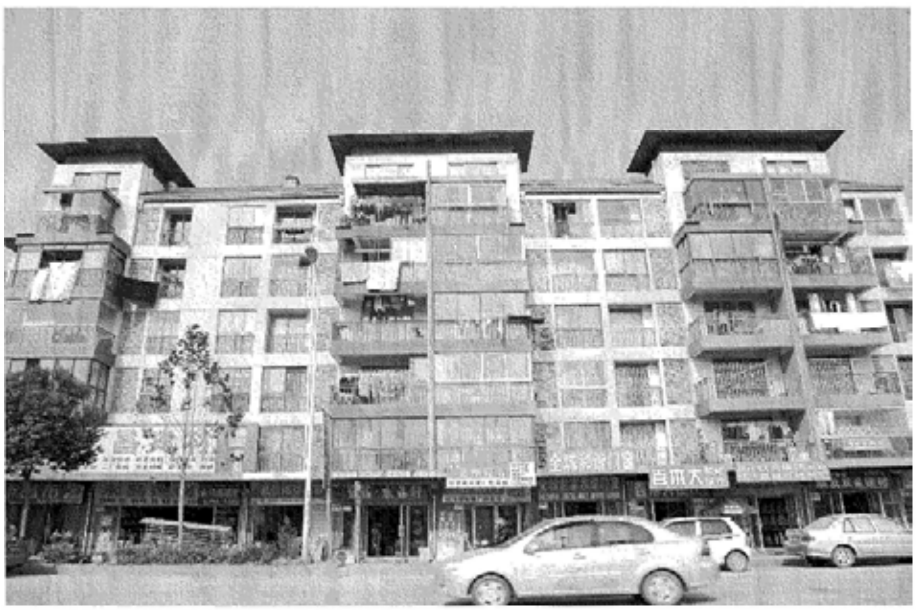

Figure3- 6: Typical facade of urban residential buildings

These form and layout similarities guarantee most residential buildings have direct sunlight if there is no shade from surrounding vegetation. But in summer, regular lines of building sometimes block the air movement, and indoor natural ventilation is insufficient.

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[28] Figure is modified from Google Map

Additionally, the huge housing estates with high density but without enough greenery make the urban heat island effects worse.

3.1.2.3 Poor building thermal performance

The general building thermal performance is not satisfactory in terms of the local severe climatic conditions. In summer, insufficient design strategies for reducing solar radiation and insufficient ventilation make the building very stuffy (Fu 1998). While in winter, the envelope insulation is not good enough to resist the outdoor coldness. There is bad tightness of windows and doors, and high heat transfer coefficient of building envelope (Fu 1998). The bad thermal performance makes the temperature difference between indoor and outdoor too small and occupants suffer both in summer and winter.

Generally speaking, during this rapid urbanization process, China urban housing conditions are very complicated and varied. The above brief description relevant to thermal environments just tries to explain the current housing background that residents inhabit, with the constraints as well as the opportunities brought by those housing conditions for adaptive thermal comfort.

3.2 Research Methods

Field studies in the local residents' living environments and the associated statistical processing are employed as the main research methods. The fundamental feature of this field research design is the comparision, in time and space, of subjective thermal comfort questionnaire response from occupants with corresponding objective indoor and outdoor climate observation (Cândido 2010). As mentioned in Chapter 1 (Figure 1-1), three steps of field data acquisition, data analysis and results interpretation are the basis for the final research outcomes. Detailed methods for investigation design, data acquisition and data treatments are unfolded in the following sections.

3.2.1 Investigation design

For this study, the whole investigation is divided into two parts. Investigation I emphasizes residents' thermal behaviours and thermal requirements in daily life through the use of Questionnaire A; Investigation II investigates residents' subjective thermal perception of their thermal environments through Questionnaire B and comprehensive indoor climatic measurements. The respondents who have participated in Investigation I are invited join the Investigation II, and the results of Investigation I will provide context for the results of Investigation II.

3.2.2 Data acquisition

Field studies try to collect data through thermal questionnaires, physical parameter measurements, interviews with and observation of respondents. There are two kinds of data records. One is the quantitative measurements of physical environments and thermal attitudes, such as outdoor climatic conditions, indoor climatic conditions, and respondents' thermal perception assessments; and the other one is the qualitative record of respondents' non-thermal variation, housing characteristics and their behavioural adjustments to the corresponding thermal environments. Additionally, some identification and demographic information is required.

3.2.2.1 Data composition

The data collected in this study can be categorized into six concepts: outdoor thermal conditions, indoor thermal conditions, subjective thermal perception, daily thermal behaviours, housing characteristics and personal non-thermal variations. All these six concepts and their corresponding variables are listed in the Table 3-1 and more detailed data composition and coding conventions are given in Appendix A.

Table3- 1: Data composition of concepts and variables

Concepts	Variables
Outdoor thermal condition	Air temperature,
	Relative humidity,
	Air velocity;
Indoor thermal condition	Air temperature,
	Radiation temperature,
	Relative humidity,
	Air velocity;
Subjective thermal perception	Thermal sensation vote,
	Thermal comfort vote,
	Thermal preference vote,
	Thermal acceptability vote
	Air movement sensation vote,
	Humidity sensation vote;
Daily Thermal behaviours	Environmental controls and behavioural adjustments
	Triggering temperature
	Heating/cooling patter
	Dressing habit
	Attitude to choosing heating/cooling methods
Housing characteristics	Housing plane,
	Opening design,
	Heating/cooling equipments, etc.;
Personal non-thermal variation	Age, gender, economic conditions, etc.

In addition to the above variables, metabolic rate and insulation afforded by clothing and chair are required. The estimation of clothing value and metabolic rate according to 2005 ASHRAE handbook (ASHRAE 2005) is shown in Appendix B and Appendix C. Also, some thermal indices, such as "ET", "SET", "PMV" and "PPD", are calculated adopting existing software "UC Berkeley Thermal Comfort Program" developed by Charlie Huizenga. There are two purposes for the involvement of those thermal indices. One is to make a better comparison with other research results, and the other is to assess their ability to predict occupants' adaptive thermal comfort in the studied climatic and housing conditions.

3.2.2.2 Selection of climatic conditions

With the focus on adaptation to conventionally defined uncomfortable thermal environments, the main field investigations were conducted in the 2007 summer and the 2008 & 2010 winters. The general climatic information during the investigation period is listed in the Table 3-2. Measured data were collected from an Automatic Hubei Observatory[29], and China Standard Weather data (CSWD) were collected from National Meteorological Information Center of China Meteorological Administration[30]. Through the comparison of these two sets of climatic data, it was found that the air temperature, relative humidity, air velocity and wind direction in survey periods (from 26th, July to 3rd, August, 2007; from 23rd, December to 28th December, 2008; from 17th, January to 4th, February, 2010) were typical enough to represent local climate of Wuhan both in summer and winter. In summer, the mean air temperature was around 31℃ to 34℃ and the relative humidity around 60%; in winter; the mean air temperature was around 4℃ to 7℃ and the relative humidity in the range "50%~90%". In other words, the results from this study will reliably represent residents' real response to the local hot-humid and cold-damp climate.

Detailed comparisons of hourly meteorological data including air temperature, relative humidity, and wind velocity and direction are displayed in Appendix D.

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[29] Website: http://zdz.hbqx.gov.cn

[30] National Meteorological Information Center, C. M. A. and T. U. Department of Building Science (2005). Special Meteorological Data for Building Thermal Environment Analysis in China. Beijing, China Architecture and Building Press.

Table3- 2: Comparison of observed weather during survey periods against Standard Weather Data for the same periods

Dates	2007 Summer (26th, July to 3rd, August)		2008 Winter (23rd, Dec to 28th Dec)		2010 Winter (17th, Jan to 4th Feb)	
	Measured data	CSWD	Measured data	CSWD	Measured data	CSWD
Mean air temperature (℃)	31.7	33.8	4.14	5.41	6.35	4.93
Mean relative humidity (%)	59.8	58.5	52.7	68.6	81.8	84.5
Mean air velocity (m/s)	1.6	1.4	1.1	1.0	1.9	1.0
Prevailing wind direction	SW	SW	N	N	N	N

Notes: SW(South-west); N(North)

3.2.2.3 Sample selection and preparation

3.2.2.3.1 Non-probability sampling

Probability sampling is not adopted in this survey because the results are not generalized to the whole population of Wuhan. Also, there is no preceding adaptive thermal comfort study conducted anywhere in the world that adopts probability sampling because the population is difficult to define in this kind of survey and completed sampling list is hardly possible. CUHK group also explained that some other limitation of resource, cost and time which make probability sampling not feasible to be carried out in the field survey of thermal comfort (CUHK 2008). What the researcher can do is to assume the target population is homogenous in terms of their subjective response on thermal stimulus (this is the key objective of this study) and do some inferential analysis from the selected sample. Therefore, although probability sampling is not attempted, aided by some statistical techniques, the objectives of the survey as mentioned in the Chapter 1 still could be attained and the results could be inferred to the intended scope of the survey.

3.2.2.3.2 Sampling of households and individuals

Although probability sampling is not employed in this study, sampled households and individuals are required to be as close to the delineation of aimed population as possible, as this requirement can improve the applicability of this research's results.

When choosing the households and individuals for this study the following criteria were applied: (i) windows have to be easy to access and operate; (ii) rooms are not air-conditioned or centrally heated ; (iii) the occupants have lived in Wuhan (or HS&CW climatic zone) for more than 4 years; (iv) the occupants are in good health and are capable of expressing their thermal response properly and (v) the occupants could freely adapt their clothing to the indoor and/or outdoor thermal conditions (de Dear 1998).

More than 500 households from seven main urban districts, Jiangan, Jianghan, Qiaokou, Hanyang, Wuchang, Hongshan, and Qingshan, were interested in this adaptive thermal comfort research and participated. Finally, 309 households in summer and 119 households in winter participated in Investigation I and gave valid answers to the Questionnaire A. 91 individual from 71 households joined in Investigation II and supplied valid 513 sets of data information to Questionnaires B[31].

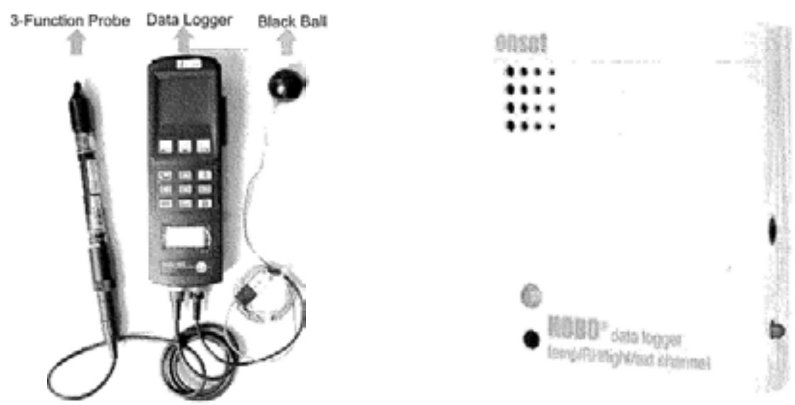
3.2.2.4 Instruments

Four physical variables including air temperature, radiation temperature, air velocity and humidity, selected because of their possible influence on the heat exchange rate were measured in this study (Fanger 1970; Auliciems 1972). Indoor thermal information and nearby outdoor thermal information (always at the open balcony or outside the window) is collected through instantaneous measurements at the same time as the questionnaires were

[31] A set of data means that one set of thermal perception votes corresponding to measured instantaneous thermal environment.

distributed. Meanwhile, regional meteorological information is obtained from the Automatic Hubei Observatory[32].

Because of the shortage of equipment and for the convenience of measurement, this study only records physical parameters at one height above the floor (1.1m for standing subjects or 0.6m for sitting subjects) in the middle of living space. Air temperature and relative humidity are automatically recorded by portable electronic devices including Testo 400 and HOBO U12 (Figure 3-7).



Left: Testo 400 plus 3-Function Probe   Right: HOBO U12 Temp/RH/Light/External Data Logger

Figure3- 7: the sensors and data logger in the measurement

The Testo400 has (1) a 3-function sensor probe for the measurements of air temperature, humidity and wind speed; (2) external sensor for globe temperature recording with one 38mm diameter black Ping-pong ball; and (3) TESTO 400 data logger for instant processing of the measured data (Figure 3-7 left). Measuring range of temperature is -40℃ to 150℃ with the accuracy of ±0.2℃, measuring range of velocity is 0m/s to 20m/s with accuracy of ± 0.03m/s; and the range of relative humidity is 0 to 100 %RH with the accuracy of 1%. Because of cell capacity, Testo only can continuously record data for around 12 hours

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[32] http://zdz.hbqx.gov.cn/zhindex.php

with one minute sampling and logging time, and it can record air temperature, globe temperature, relative humidity and air velocity simultaneously.

The HOBO U12 is a four-channel electronic recording device that provides temperature, relative humidity, indoor light level measurements and one external input channel (Figure 3-7 right). In this study, HOBO U12 was only employed to record outdoor air temperature and relative humidity. Its measuring range of temperature is -20℃to 70℃ with accuracy of ±0.35℃ at 0℃ to 50℃ and resolution of 0.03℃ at 25℃. The relative humidity measuring range is 5%RH to 95%RH with accuracy of ±2.5% from 10% to 90% (10℃ to 50℃) and resolution of 0.03%. HOBO U12 can continuously record air temperature and relative humidity continuously for several days.

One purpose of a globe temperature recording is to calculate mean radiation temperature with the supplement of air temperature and air velocity information, adopting the ASHRAE HoF formula as follows [33] and detailed equation explanation is provided in Appendix G.

$$T_{mrt} = \left[(t_g + 273)^4 + \frac{1.10 * 10^8 * V^{0.6}}{\varepsilon * D^{0.4}} (t_g - t_a) \right]^{0.25} - 273 \qquad \textbf{\textit{(3-1)}}$$

All the equipment used in this study are ISO certified, and cross calibrated in the laboratory before the field measurements. The timing systems in the equipment were regularly synchronized with the Hubei Observatory's timing system.

[33] de Dear, R., G. S. Brager, et al. (1997). Developing an adaptive model of thermal comfort and preference. Sydney & Berkeley, Macquarie Research Ltd., Macquarie University & Center for Environmental Design Research, University of California: P42

3.2.2.5 Questionnaire design

3.2.2.5.1 Investigation I

Questionnaire A used in this investigation was developed with emphasis placed on residents' self estimate of their thermal requirements in daily life and the description of their daily thermal behaviors. This questionnaire covers five categories of information including the sample's basic personal information, housing characteristics, living habits relevant to thermal environments, adjustment strategies to avert thermal discomfort, and attitude on heating/cooling methods. Each category includes several questions for information acquiring as listed in Table 3-3.

Personal information covers respondents' age, gender, family composition, family income and electricity bill. Housing characteristics comprise housing floor area, plan layout, housing type and heating/cooling equipments. Living habits related to thermal environment include the trigger temperature for switching heating/cooling devices, heating/cooling patterns and daily dressing habits. Adjustment strategies are investigated through questions about usage frequency of 18 kinds of behaviour, separately in winter and summer. Finally, attitude to choosing heating/cooling methods are acquired through priority ranking questions. The fully developed questionnaire is shown in Appendix E1 to Appendix E4.

Table3- 3: Questionnaire A design for investigation I

Concept	Abbreviation	Questions
Personal information	Age	How old are you?
	Gender	What is your gender?
	Duration in home	How many hours do you stay at home per day on average?
	Family composition	How many generations are living together in your house/apartment? How many people are living in your house/apartment permanently now?
	Family income	What is the average income per person in your family?
	Heating/cooling bill	How much money need you pay for the heating/cooling per month on average in your family?

Housing characteristics	Floor area	What is the "gross floor area" of your house/apartment?
	Layout	What is your house/apartment layout (room composition)?
	Housing type	What kind of building type is your house/apartment?
	Heating/cooling equipments	What type of air-conditioner do you use in your house/apartment?
		What kind of additional heating/cooling equipment do you use in your house/apartment except for the air-conditioner?
Living habits related to thermal environment	Trigger temperature switching on heating/cooling	How low/high does temperature decrease/increase to, before you will switch on the air-conditioner?
		How low/high does temperature decrease/increase to, before you will switch on other heating/cooling equipment excluding the air-conditioner?
	Thermal comfort purpose	What kinds of activities require more comfortable thermal environments in your daily life?
		When do you need more thermal comfort in home?
	Open window and doors habits	What kind of windows & doors do you like to keep open?
	Heating/cooling pattern	What type of air-conditioner do you use in your house/apartment?
		Do you switch on heating/cooling equipment in all rooms or in the rooms as you need?
		Do you switch on heating/cooling equipment 24 hours or just as you need?
	Dressing habit	What is your dressing habit in home in winter?
Adjustments behaviors to thermal discomfort (winter/summer)	FAB1	Closing doors (winter)
		Opening doors for natural ventilation (NV) (summer)
	FAB2	Closing windows
		Opening windows for NV
	FAB3	Increasing clothes
		Reducing clothes
	FAB4	Increasing chair and bed's insulation
		Reducing insulation, such as bamboo mat and sheets (clothes excluded)
	FAB5	Hot food and drink
		Cold or frozen food and drink
	FAB6	Switching on semi-portable heater, such as electrical heater, coal stove, etc
		Mechanical fan
	FAB7	Air-conditioner for heating
		Air-conditioner for cooling
	FAB8	Using portable heat source, such as hot-water bottle, etc
		Swimming or shower
	FAB9	Basking in the sunshine
		Keeping calm
	FAB10	Increasing the probability of using warmer rooms
		Reduce usage of hotter space
	FAB11	Switching on fixed heaters, such as heater under floor or some central heating
		Adjusting thermostat
	FAB12	Improving the building insulation or tightness
		Curtain or shutter
	FAB13	Doing more exercises
		Reducing activities
	FAB14	Reducing outdoors activities
		Vegetation cooling
	FAB15	Waking up later and going to bed earlier
		Evaporation effect

	FAB16	Body posture change
		Walking out in the evening
	FAB17	Hot bath or hot footbath
		Sleeping outdoors in the night
	FAB18	Lower thermal comfort expectation (more tolerance)
Attitude to choosing heating/cooling methods	Driving factors for choosing heating/cooling methods	What properties determine your choice of heating/cooling methods? Health; Safety; Convenience; Thermal performance efficiency; Economic efficiency.

3.2.2.5.2 Investigation II

Investigation II was conducted through field measurements of occupied thermal environments and occupants' thermal perception in homes. Questionnaire B employed in this investigation was developed with emphasis on occupants' subjective perception of real thermal stimulus and it covers three sections of information, which is a classic "right here right now" survey,. Part one is building information from investigated families; part two, the key part, is occupants' information including subjective thermal perception votes, activity-description and clothing records; part three is the indoor and outdoor climatic information. Detailed organization of this questionnaire can be found in Appendix E5 to Appendix E8.

For the part two, thermal perception comprises four variables rather than just one. as advised by Auliciems and Brager (Auliciems 1981; Brager, Fountain et al. 1993). Brager et al pointed out that those indirect measurements of dissatisfaction (including "thermal sensation", "thermal comfort" and "thermal preference") produce widely different assessments of the acceptability of a given environment in the field, and recommend that a direct item on "thermal acceptability" should be included. Therefore, in this study, four variables of thermal sensation, thermal comfort, thermal preference and thermal acceptability were obtained through standard questions on the same occasion. Meanwhile, humidity and air movement sensation also are required for more specific investigation of the subjective response to indoor humidity and air-velocity.

The ASHRAE thermal sensation scale and the McIntyre Thermal Preference scale were used. Four-point Likert scales acquired thermal comfort and thermal acceptability; five-point Likert scales were adopted for humidity and air movement sensation. All the subjective scales are formatted as continuous scales in this study, so allowing non-integer ratings to be given (Table 3-4). Real numbers were given to these scales for the further regression analysis as showed in Table 3-5. For thermal comfort research, no published reference could be found to do translation correction between English and Chinese, therefore same true thermal perception is given to paired English scaling and Chinese scaling.

Table3- 4: Questions for thermal perception using different scaling

Variable	Questions
Thermal sensation	How do you feel the current thermal environment? Cold — Cool — Slightly Cool — Neutral — Slightly Warm — Warm — Hot
Thermal comfort	In generally, how do you feel the current thermal comfort? Comfortable — Slightly warm uncomfortable — Hot uncomfortable — Extremely hot uncomfortable (summer) Comfortable — Slightly cool uncomfortable — Cool uncomfortable — Extremely cold uncomfortable (winter)
Thermal preference	How do you want to change the current thermal environment? Warmer — No change — Cooler
Thermal acceptance	Can you accept the current thermal environment only base on your individual concerns? Acceptable — Slightly unacceptable — Unacceptable — Extremely unacceptable
Humidity sensation	How do you feel current humidity? Too damp — A little damp — Just right — A little dry — Too dry
Air movement sensation	How do you feel current wind velocity? Too still — A little still — Just right — A little windy — Too windy

Table3- 5: Thermal scaling and given real number

Variable	Scale and given true number						
Thermal sensation (ASH)	Cold -3	Cool -2	Slightly Cool -1	Neutral 0	Slightly Warm 1	Warm 2	Cold 3
Thermal comfort (COMF)	Comforta ble 0	Slightly warm/cool uncomfortable 1	Hot/Cold uncomfortable 2	Extremely hot/cold uncomfortable 3			
Thermal preference (MCI)	Warmer 1	No change 2	Cooler 3				
Thermal acceptance (TSA)	Acceptabl e 0	Slightly unacceptable 1	Unacceptable 2	Extremely unacceptable 3			
Humidity sensation (HUS)	Too damp 1	A little damp 2	Just right 3	A little dry 4	Too dry 5		
Air movement sensation (AMS)	Too still 1	A little still 2	Just right 3	A little windy 4	Too windy 5		

The ASHRAE thermal sensation scale is a recognized tool, used in both laboratory and field studies, and adopting it is essential for comparing these Wuhan results to others' studies, even though some interpretation variation is inevitable between different languages (Humphreys 2008). The conventional assumptions are that (1) "neutral" thermal sensation vote corresponds to optimal conditions perceived, and (2) the three central categories of the thermal sensation scale (slightly cool, neutral, and slightly warm) represents comfort, or acceptability.

The McIntyre thermal preference scale is used as a more direct assessment of ideal conditions, and the occupant is asked to indicate how they would like to change the current thermal environment (warmer, no change, cooler) (McIntyre 1978). The employment of thermal preference in this study is to assess optimum comfort conditions expressed as the preferred temperature (whatever temperature index is used), and to compare simultaneous votes of thermal sensation and preference to determine whether "neutrality" actually represents the optimal thermal response for the local residents.

Four-point acceptability scales and thermal comfort are adopted to obtain respondents' direct estimation of their corresponding thermal environments. ASHRAE Standard 55 defines the comfort zone as the zone in which 80% or more of the occupants would be in the central three thermal sensation categories of the ASHRAE scale (ASHRAE 2010). In this study, direct thermal acceptability assessment allows occupants make their own judgments about whether the physical thermal condition and associated thermal sensation are acceptable, and determine whether central three categories of thermal sensation scales is appropriate place to draw the acceptability line for local residents. Direct thermal comfort questions attempt to get a broader look at the thermal state of the occupant and to distinguish thermal sensation from overall comfort. The purpose of employment of thermal comfort scale is to check whether the central three categories of thermal sensation are appropriate to determine occupants' general comfort state in the real living environments of Wuhan.

The questionnaires (A&B) employed in this study were tested in pilot study in Wuhan in 2007 summer in local residents' home and got several revisions before conducting field survey.

3.2.2.6 Investigation protocol

For Investigation I, respondents were required to answer questionnaire A through the internet or in a face-to-face interview at their convenience. Same questionnaires were distributed and the answers were coded and prepared for analysis.

For the Investigation II, the investigation protocol was much more complicated because of the several simultaneous tasks involved in the field. In this study, the author carried out these tasks with the assistance of graduate students from local universities. The investigation protocol in each family entailed following steps.

Firstly, the family was informed of the intention to investigate their adaptive thermal comfort by taking some physical parameter measurements and administering a questionnaire at their home.

Equipment: One set of Testo400 was put in the central position of investigated room (always the living room) at 0.6m height for seating occupants (1.1m height for standing occupants). After approximate 30 minutes stabilization, the Testo 400 started to record the indoor ambient thermal environment automatically while the occupants were answering the thermal questionnaire. The HOBO was placed on the open balcony to record the outdoor ambient temperature and humidity.

Questionnaire distribution: After setting-up all the equipment, the investigator began the interview and questionnaire distribution with family members. In most cases, one or two of the adult family members would answer the questionnaire, by ticking or by oral presentation in. Respondents could answer Questionnaire B (part 2) repeatedly with minimal 15 minutes interval time.

Observation and measuring: After completing the questionnaires, making observations, taking measurements, as well as conversing with family members, the investigator recorded the housing characteristics, including housing plan, the location of doors and windows, heating/cooling equipments, etc.

Usually, two investigators needed around 3 hours to finish the survey in each household, and 4 to 8 copies of thermal perception questionnaires were obtained. Away from residents' home, the investigators would download the data collected through equipment and match them to occupants' questionnaire answers as well as to the observatory climatic data for subsequent data processing.

3.2.2.7 In-depth case study

Based on the theory of Contextualism and Perspectivesm, human behaviours are necessarily grounded in a perspective and dynamic context (Rosenthal and Rosnow 1991). The in-depth case study employed in this study is to explore why and how those adaptive behaviours happen. The interview conducted at the interviewees' home focused on three relevant factors: housing characteristics, economic conditions and living habits. The conversation is laid out to discern occupants' basic activities at home and their attitude to the thermal environments they exposed to. Sometimes the conversation was in the form of supplementary anecdote for this study.

The conversation between investigator and interviewees was recorded to help recall the interview situation. Most information from the interview was collected through Questionnaire A and free conversation within the topic of thermal comfort. The investigators encouraged residents explain more about their behaviours related to thermal environments. After the interview, the investigator would guide the family members to answer questionnaire B and leave the part two sheet for them to fill out. Meanwhile, measuring instruments were left working at their home during the following days.

Three urban households and six households who had come to Wuhan from a country area participated in the in-depth case study.

3.2.3 Data treatment

The analytical data treatment in this study begin with compilation, coding and inputting of raw data gathered from different sources, which included documentation, on-site walkthrough, measurements, observation, interviews and questionnaire survey, and then the data were sorted and summarized into a dataset suitable for computer analysis. The analysis was done with the aid of the Statistical Package for Social Sciences (SPSS) software (version 15).

3.2.3.1 Data processing

For Investigation I, raw data from questionnaire A were complied and coded into an EXCEL spreadsheet. After eliminating data-errors, they were converged into an SPSS file for initial descriptive statistical analysis.

For the Investigation II, converting the raw data from the data acquisition system into an SPSS file for subsequent analysis required several steps as displayed in Figure 3-8.

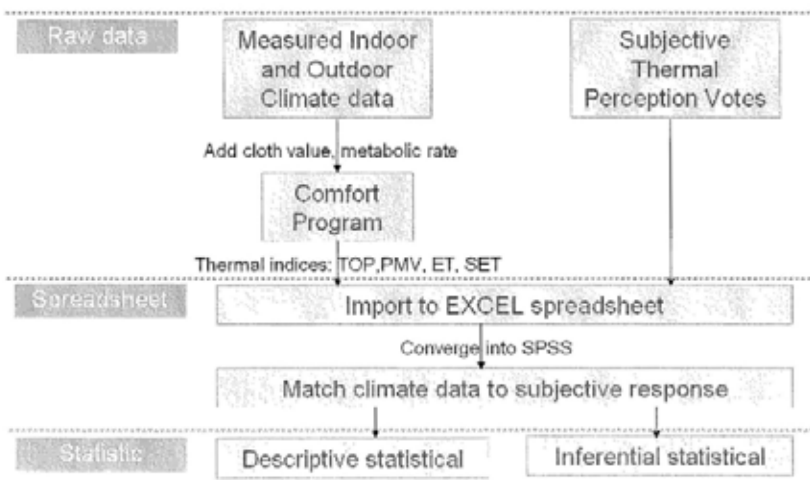


Figure3- 8: Data processing steps

Raw data from measuring indoor and outdoor climate, subjective thermal perception votes, clothing value and metabolic rate, which had been collected through Questionnaire B, were complied and coded into an EXCEL spreadsheet. Then calculated thermal indices using the Comfort Program also were added to the spreadsheet. After converging into an SPSS file and eliminating data-errors, the completed SPSS file contained rows representing each respondent with their demographic information, thermal perception votes, indoor and outdoor climate variables, and corresponding calculated thermal indices. Finally, descriptive and inferential statistical techniques are employed to analyse the data. This analysis procedure included exploring the correlations within the data, as explained below.

3.2.3.2 Descriptive statistical analysis

The analytical procedures of the studying variables began with describing, displaying and summarizing of the data collected from the questionnaire survey and field measurements. The purpose of this descriptive statistical analysis is to describe the characteristics of analysis units, including measures of central tendency, measures of variation or dispersion, and measures of position and location for a given characteristic.

For this study, descriptive statistics techniques, including mean, frequency, percentage and standard deviation, were employed in the data analysis. "Frequency" and "Percentage" of gender, age, income, thermal behaviors, etc, are employed to describe the characteristics of respondents. "Mean" is employed to describe the central tendency of measured units, such as the mean of air temperature, radiation temperature, relative humidity, air velocity, clothing level, metabolic rate and subjective thermal perception votes both in summer and winter. The Variance and Standard Deviation are employed to describe the variability of measured units including all the objective thermal variables mentioned above and subjective thermal perception votes including thermal sensation, thermal comfort, thermal preference and thermal acceptance.

3.2.3.3 Inferential statistical analysis

The inferential statistical techniques used in this study included Regression Analysis and Pearson's Product-Moment Correlation Coefficient (r) . These methods have been widely employed to study the interrelationship within subjective thermal perception and thermal indices by the research communities of adaptive thermal comfort. See, for example: Linear Regression[35](Humphreys 1975), Polynomial Regression[36](de Dear, Brager et al. 1997) and Probit Regression[37] (Ballantyne, Hill et al. 1977; Kwok 1997). Following Table 3-6 displays the possible regression analyses between thermal perception variables (the columns), and thermal index variables (the rows). In this study, the regression modelling will be tested to quantify how the occupants' thermal perception correlated with different thermal indices.

Table3- 6: Correlations between thermal perceptions with different thermal indices

	Indoor thermal environments	**Calculated thermal index**	
	TOP	SET	PMV
Thermal sensation	Linear regression analysis	Linear regression analysis	Linear regression analysis
Thermal comfort	Linear regression analysis & Polynomial regression analysis	Linear regression analysis	Linear regression analysis & Polynomial regression analysis
Thermal preference	Probit regression analysis	Probit regression analysis	Probit regression analysis
Thermal acceptability	Polynomial regression analysis	Polynomial regression analysis	Polynomial regression analysis

[35] Linear Regression is the simplest way to display the dependence of thermal perception on thermal stimulus. It was first applied by Thomas Bedford in 1936. It has been used in the adaptive thermal comfort study for more than thirty years as for example in the meta-analysis addressed by Humphreys.

[36] Polynomial Regression is employed to evaluate thermal acceptability on temperature and other thermal indices rather than Linear Regression because there should be a maximum acceptability value as temperature (or other indices) pass through thermal neutrality.

[37] Probit Regression is employed as analysis method to evaluate thermal preference on thermal stimulus, and it was originally drawn from studies of threshold pesticide levels and insect kill rates. It offers the advantage of being able to handle data that are shifted from a central tendency over the neutral category.

3.3 SUMMARY

The methods, instrumentation, measuring protocols, and data treatments used in this study originally come from those used in recent field investigations of thermal comfort in building environments, which have been examined by the international research communities. The new approach taken here applied these conventions to the housing setting and enlarged the investigation of local residents' thermal behaviors and their thermal requirements in order to explore and understand the local residents' adaptive thermal comfort in Wuhan.

CHAPTER 4

RESULTS

This chapter presents the results of the study in four sections. Section 4.1 provides descriptive thermal behavior measurements of two investigations centering on demographic information about the respondents, housing characteristics and daily thermal behaviors; section 4.2 summarizes the measured indoor thermal environments and compares the results with the prescriptions of conventional thermal comfort zones; section 4.3 presents occupants' subjective thermal perceptions including thermal sensation, thermal comfort, thermal preference and thermal acceptance as well as humidity and air movement sensation; last, section 4.4 displays the results from in-depth case-studies including reported housing characteristics, family economic conditions, living habits and their real thermal perception.

4.1 DESCRIPTIVE THERMAL BEHAVIOUR MEASUREMENTS

4.1.1 Investigation I

4.1.1.1 Sample size

After eliminating child respondents (younger than 14 years), elderly respondents (older than 75 years) and respondents have not been used to local climate (in this study, residents are assumed to be not used to local climate until they have lived in the same climatic zone more than 4 years), 309 households in summer and 119 households in winter gave valid answers to the Questionnaire A. In this investigation, each adult respondent represents one household, and some households took the survey both in winter and summer. Table 4-1 displays those respondents' information on gender, age, and the duration of residence in the HS&CW climate conditions.

During Investigation I, male respondents were a little more frequent than female respondents (59.5% male in summer and 57.1% in winter). No matter whether male or female, more than ninety percent of them were in the age between 14 to 44 years and around eighty percent of respondents had lived in Wuhan (or same climatic zone) more than 12 years.

Table4- 1: Sample summary for Investigation I

		Total (n=428)		Summer (n=309)		Winter (n=119)	
		Sample size	**Percentage**	**Sample size**	**Percentage**	**Sample size**	**Percentage**
Gender	Male	252	58.9%	184	59.5%	68	57.1%
	Female	176	41.1%	125	40.5%	51	42.9%
Age (years)	14-44	388	90.7%	279	90.3%	109	91.6%
	45-59	34	7.9%	24	7.8%	10	8.4%
	60-74	6	1.4%	6	1.9%	0	0
Duration (years)	4-12	90	20.0%	75	24.3%	15	12.6%
	>=12	338	80.0%	234	75.8%	104	87.4%

4.1.1.2 Family composition, income and expense for heating/cooling

A summary of respondents' family composition, monthly income and their maximal expense for heating/cooling is given in Table 4-2 and Figure 4-1, 4-2, 4-3. Generally, the majority of investigated households comprised 3~4 persons and 1~2 persons whether in summer (68.3%, 22.7%) or winter (74.8%, 16.0%). Around eighty percent of their individual monthly income levels were in the central three categories (800~5000RMB/person month). This result is consistent with the average family incoming of 1523.81RMB per person per month published by Wuhan Statistic Bureau in 2009[38].

[38] Source from: http://www.whtj.gov.cn/documents/tjnj2009/index.htm

Around 34% households spent 100-200 RMB for heating in the coldest month and cooling in the hottest month, around thirty percent households spent 200-300 RMB and fifteen percent households spent 300-500 RMB for it. Therefore, it is can be assumed that for a typical three-person household, maximally they spent one twentieth of their income for heating or cooling. Although electricity bills cannot exclusively display the usage frequency of heating/cooling equipment, it is a good indicator to show how much money residents spend for their thermal comfort.

Table4- 2: Summary of family income and heating/cooling expense

		Summer (n=309)		Winter (n=119)	
		Sample size	**Percentage**	**Sample size**	**Percentage**
Family composition (person)	**1-2**	70	22.7%	19	16.0%
	3-4	211	68.3%	89	74.8%
	5-6	21	6.8%	10	8.4%
	7-8	3	1.0%	1	0.8%
	>8	4	1.3%	0	0%
Average income /person/month (RMB)	**Missing data**	5	1.6%	0	0.0%
	<800	17	5.5%	0	0.0%
	800-1500	70	22.7%	15	12.6%
	1500-3000	108	35.0%	49	41.2%
	3000-5000	62	20.1%	26	21.8%
	5000-10000	28	9.1%	17	14.3%
	>10000	19	6.1%	12	10.1%
Maximal expense for heating/cooling (per family per month) (RMB)	**0-50**	11	3.6%	12	10.1%
	50-100	39	12.6%	14	11.8%
	100-200	105	34.0%	40	33.6%
	200-300	89	28.8%	33	27.7%
	300-500	57	18.4%	15	12.6%
	>500	8	2.6%	5	4.2%

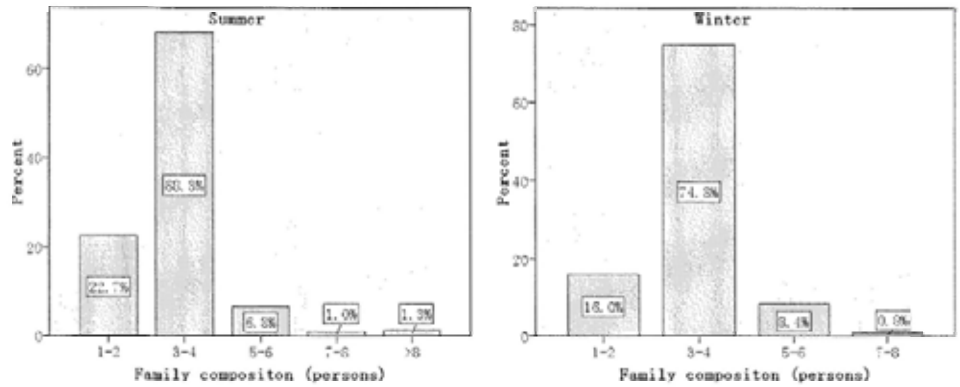


Figure4- 1: Distribution of family composition by season

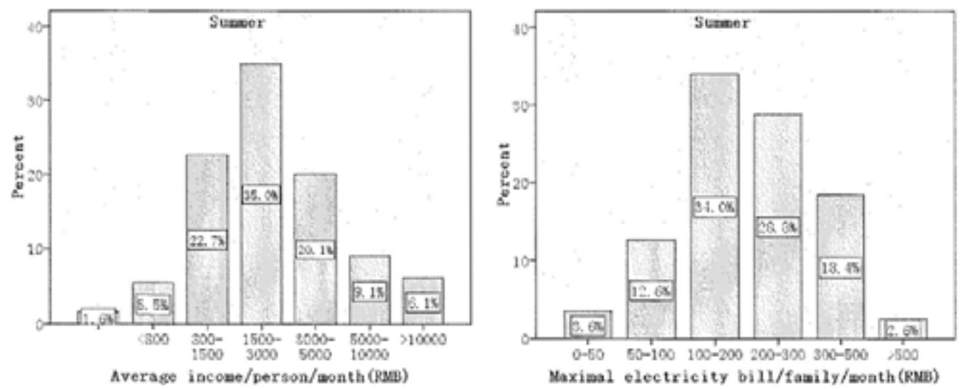


Figure4- 2: Distribution of family income and cooling expense in summer

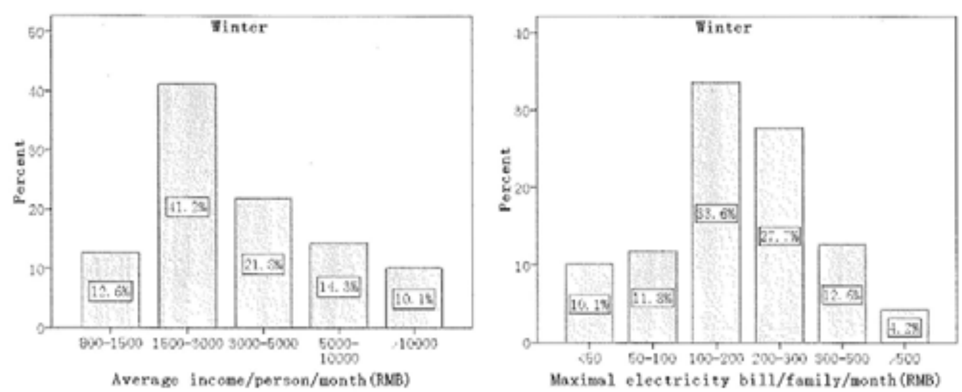


Figure4- 3: Distribution of family income and heating expense in winter

Based on the information of family composition and average income, total family income can be roughly established. Pearson correlation analysis shows that there is positive but weak correlation between total family income and maximal expense for cooling ($r=0.298$, $p<0.001$) and heating ($r=0.205$, $p=0.025$) (Table 4-3). It indicates that wealthier families would spend more money for maintaining indoor thermal comfort.

Table4- 3: Correlation between total family income and maximal expense for heating/cooling

Summer

		Maximal expense	Total family income
Maximal expense	**Pearson Correlation**	1.000	.298(**)
	Sig. (2-tailed)	.	.000
	N	309	309

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

Winter

		Maximal expense	Total family income
Maximal expense	**Correlation Coefficient**	1.000	.205*
	Sig. (2-tailed)	.	.025
	N	119	119

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

4.1.1.3 Housing characteristics

Table 4-4, Figure 4-4 and Figure 4-5 summarize the characteristics of the investigated housing units, and include the housing type and air-conditioner type. According to the classification of the Chinese Design Code for Residential Building (The Ministry of Construction 2003), there are four main housing types comprising low-storey dwelling (1-3 storey), multi-storey dwelling (4-6 storey), middle and high-storey dwelling (7-9 storey) and high-storey dwelling (10 and more than 10 storey). During this investigation, the majority of investigated housing units were 4~6 and 7~9 storey dwellings (around 75%), which stood for the real distribution of existing urban housing types in Wuhan.

It was very common that the investigated households had installed individual air-conditioners in their homes (83.3% families in summer and 86.6% families in winter). The individual air-conditioner is a very flexible and affordable heating/cooling method in the HS&CW climatic zone and therefore it is very popular in the market supply in current urban China.

Table4- 4: Summary of housing type and air-conditioner type used by investigated families

		Summer (n=309)		Winter (n=119)	
		Sample size	**Percentage**	**Sample size**	**Percentage**
Housing type	Missing data	3	1.0%	0	0.0%
	Low-storey (1-3)	39	12.6%	18	15.1%
	Multi-storey (4-6)	168	54.4%	68	57.1%
	Middle and high-storey (7-9)	63	20.4%	20	16.8%
	High-storey (<=10)	36	11.7%	13	10.9%
Air-conditioner type	No AC	20	6.5%	14	11.8%
	Individual controlled AC	259	83.8%	103	86.6%
	Central controlled AC	6	1.9%	0	0.0%
	Hybrid	24	7.8%	2	1.6%

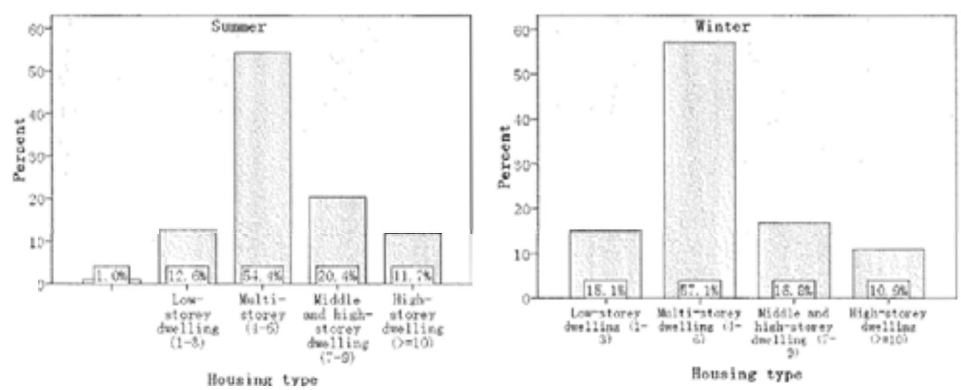


Figure4- 4: Distribution of housing type of investigated families

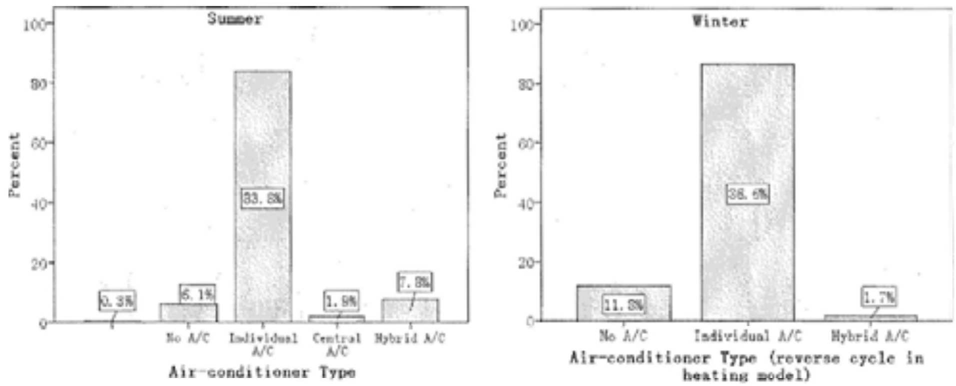


Figure4- 5: Distribution of air-conditioner type used by investigated families

4.1.1.4 Daily thermal behaviours

Investigation I put a lot of attention on the studying of respondents' daily thermal behaviors including their trigger temperature for heating/cooling, heating/cooling patterns at home, adjustments to alleviate thermal discomfort, dressing habits and attitudes to choosing heating/cooling methods. These thermal behaviors are essential to explain occupants' thermal perception collected from following Investigation II.

4.1.1.4.1 Trigger temperature for heating/cooling

Temperature is obvious and understandable thermal index, especially in daily life, air temperature is best signal to guide residents' actions relating to thermal environments. In the Investigation I, the trigger temperature for switching on heating/cooling system is acquired, in order to quantify occupants' acceptance of the thermal environment and their thermal requirements in everyday life. The trigger temperature is defined as the threshold temperature at which occupants decide to switch on heating or cooling devices, such as air-conditioners and various kinds of heaters. Figure 4-6, 4-7, 4-8, 4-9 display the cumulative percentage of trigger temperature for switching on heating/cooling devices in summer and winter. In these figures, the percentage value of each histogram represents the percentage of occupants whose trigger temperatures are higher (lower) than the termperature labbled under this histogram in summer (winter).

Majority of respondents could accept much higher and lower air temperature when compared with the comfortable temperature boundaries defined by China standards as 18℃ in winter and 26℃ in summer (JGJ 134-2001) (The Ministry of Construction 2001). In summer, about 60% respondents would not switch on air-conditioner in daily time until the temperature went up higher than 32℃, and at night time 46% would not do so. The occupants' thermal requirement was a little bit higher in night time, probably because better sleeping quality was required. In winter, 87% respondents wouldn't switch on air-conditioner for heating until the temperature fell down lower than 6℃, and 83% of respondents wouldn't switch on heating equipment, including portable electrical/gas/water heaters. Even around half respondents wouldn't adopt any heaters until temperature was lower than 0℃.

Cautiously, above results were said by respondents, and usually the temperature was imagined by them as outdoor temperature. What they really did and how the indoor temperatures distribute at those high/low outdoor temperatures should see the results derived from Investigation II.

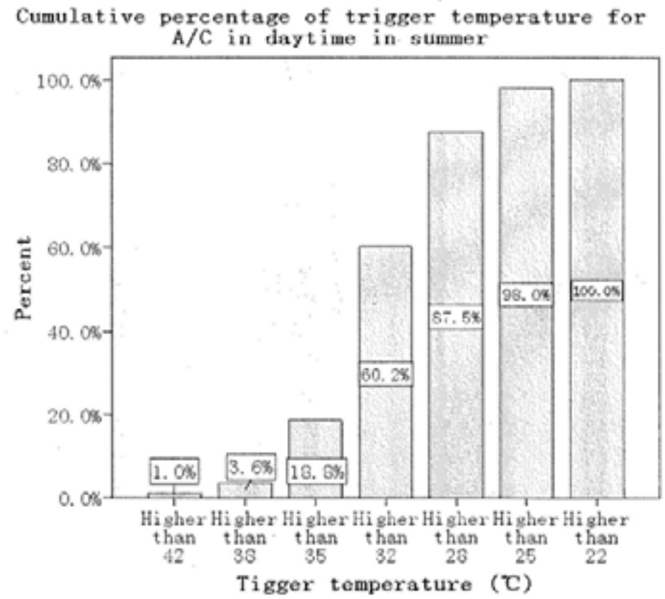


Figure4- 6: Accumulative percentage of descending trigger temperature in the daytime of switching on air-conditioner for cooling in summer

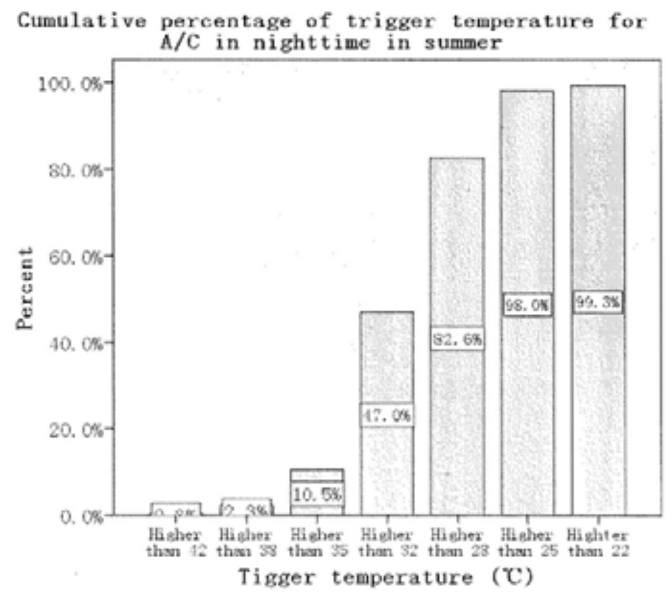


Figure4- 7: Accumulative percentage of descending trigger temperature in the nighttime of switching on air-conditioner for cooling in summer

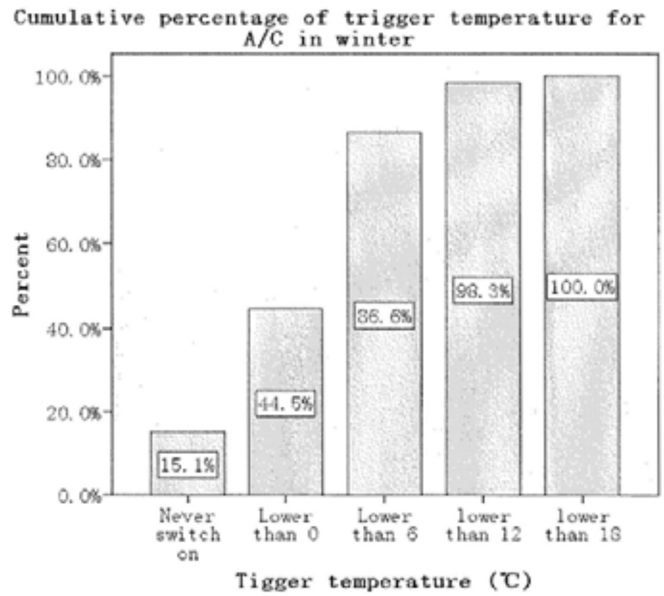


Figure4- 8: Accumulative percentage of ascending trigger temperature of switching on air-conditioner for heating in winter

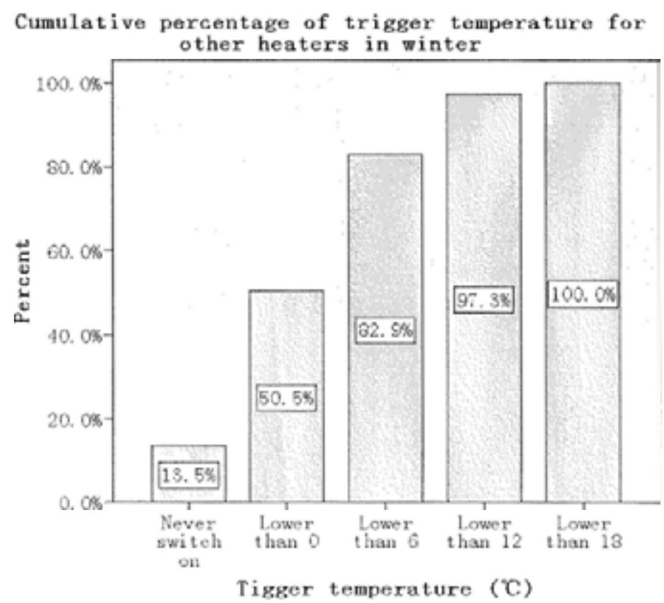


Figure4- 9: Accumulative percentage of ascending trigger temperature of switching on heaters excluding air-conditioner in winter

4.1.1.4.2 Heating/cooling patterns

The investigation of heating/cooling patterns will be helpful to understand local residents' thermal requirements for their daily life. Figure 4-10 and Figure 4-11 show that overwhelming majority of local residents had been used to intermittent and local heating patterns in winter (91% voting "during time in need" and 80% voting "one room in need") to map with occupants' activities in the necessary time and space.

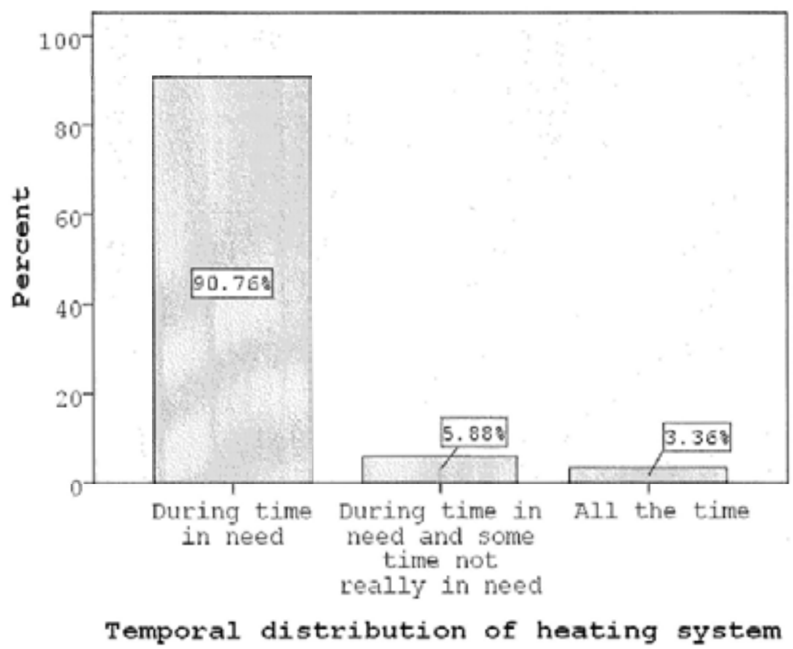


Figure4- 10: Percentage of different heating pattern in terms of temporal distribution

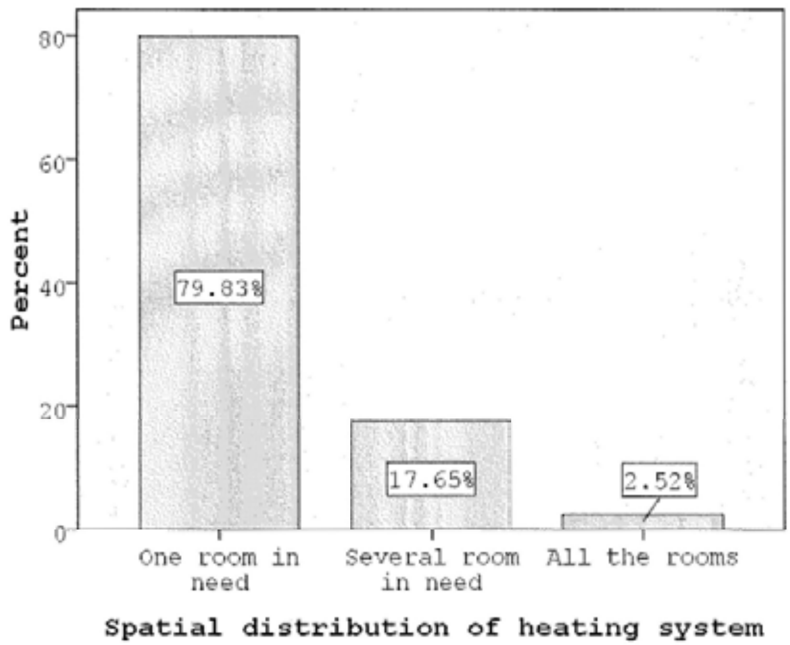


Figure4- 11: Percentage of different heating pattern in terms of spatial distribution

Figure 4-12 presents the percentage of respondents' voting for their preferred periods with air-conditioner switching on. The occupied schedule shows that respondents would like to maintain thermal comfort most frequently at noon, late afternoon, late evening, and during the night for good rest and leisure activities in summer.

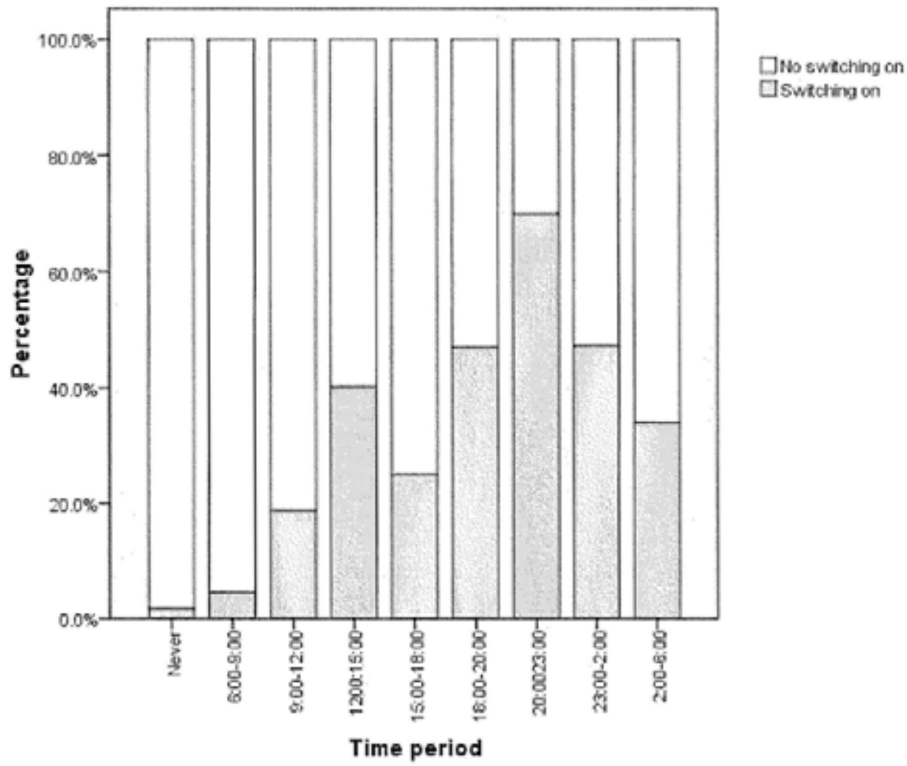


Figure4- 12: Percentage of preferred periods with air-conditioner switched on

4.1.1.4.3 Adjustments to avert thermal discomfort

A lot of research has indicated that behavioural adjustment is one significant approach to get adaptive thermal comfort (Brager, 1998). The investigation of adjustments to thermal discomfort could help us to understand why the local residents could tolerant a wider temperature range and to what extent they could adjust themselves or their surrounding environments. Figure 4-13 shows the usage frequency of different adjustments to thermal discomfort in respective seasons.

Generally, behavioural adjustments to thermal discomfort were utilized more frequently in summer compared with winter. In summer, around 80% residents would reduce insulation between human body by choice of chairs and bed (the percentage comprising votes for "frequently" and "most frequently", the same below), such as using a bamboo mat, to get more thermal comfort. And then they would adopt other means: mechanical fans, psychologically keeping calm, air-conditioners, cold food and drink, opening doors and windows for natural ventilation reducing clothes, and swimming and cool both. These means were employed frequently by more than 50% residents.

In winter, closing doors and windows was used by local residents most frequently (more than 75%), and more than 50% reported that they would avert their thermal discomfort frequently through increasing clothing, chair and bed insulation, and through hot food and drink intake.

The behavioural adjustments to reduce thermal discomfort showed broad similarities between summer and winter. In summer, controlling windows and doors for natural ventilation, increasing/decreasing clothes and insulation of chair and bed, hot/cold food and drinks were utilized by residents most frequently to reduce their thermal discomfort. Additionally, in summer, air-conditioners, mechanical fans, swimming and cool shower also were used frequently by more than half respondents. While in winter, all kinds of heater, such as electronic/gas heater, air-condition, were used widely as well as portable hot-water bottle.

The results are consistent with Heerwagen's study conducted in office buildings in USA Pacific Northwest, which showed that simple changes of occupants' behaviours were adopted widely to cope with thermal discomfort (Heerwagen and Diamond 1992). Most of those behavioural adjustments, such as changing insulation value, indoor velocity, air/radiant temperature and metabolic rate, can be explained by conventional thermal sensation prediction based on thermal balance theory. Even in the summer, the psychological adaptation of "keeping calm" also helps to achieve more comfort in mind because it is likely to reduce the metabolic rate, and so decrease the thermal load on the body.

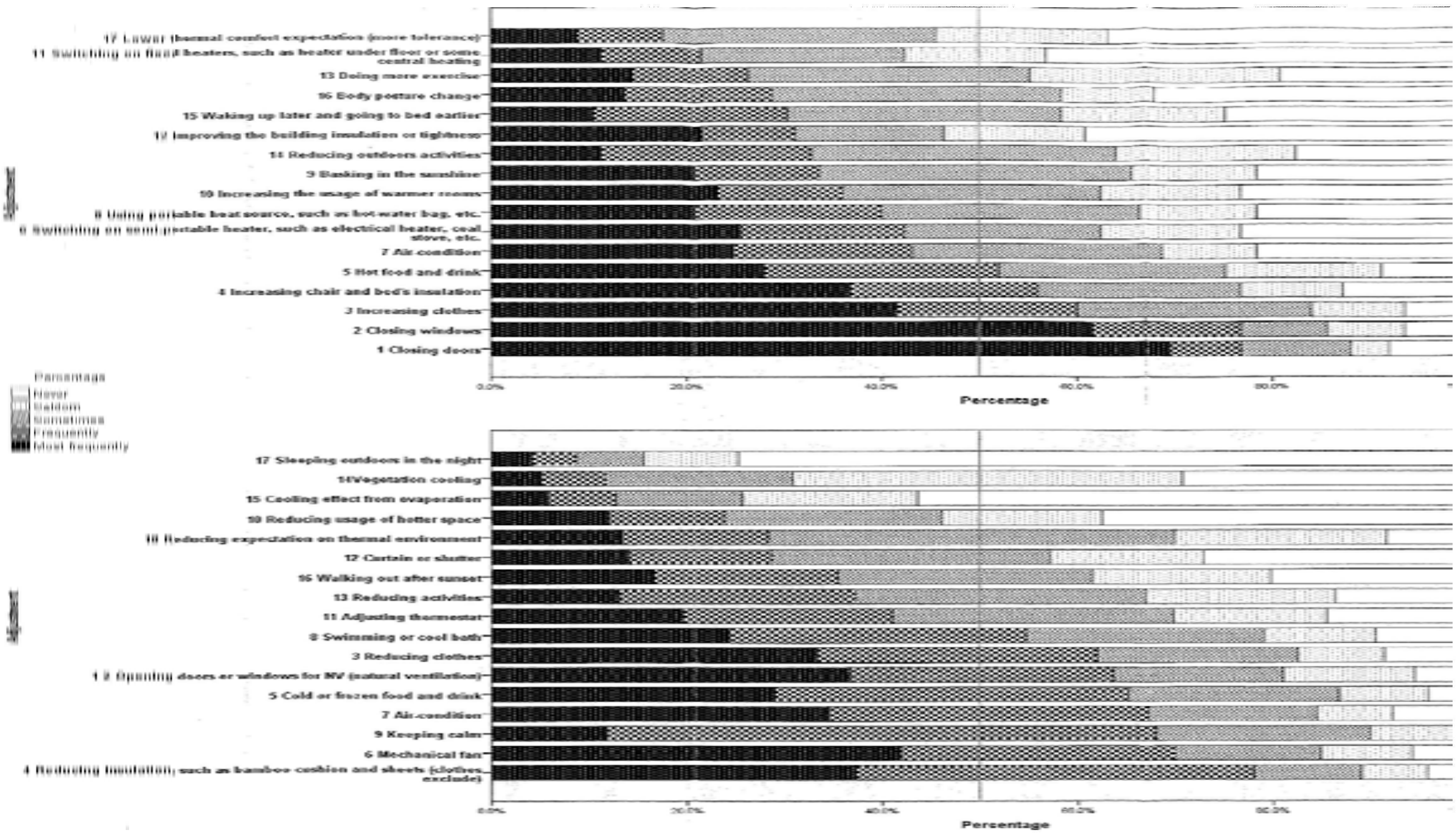


Figure 4-13-a: Frequency of different adjustments adopted by local residents in winter
Figure 4-13-b: Frequency of different adjustments adopted by local residents in summer

Figure4- 13: Frequency of behavioural adjustments to thermal discomfort in respective seasons

4.1.1.4.4 Dressing habits

The investigation of dressing habits shows that respondents liked to dress in extremely light clothes in summer and heavy clothes in winter at home. Because the clothes in winter were too heavy to calculate each garment by each garment, numeric clothing level was recorded only in summer in this investigation, as shown in Table 4-5. General description of respondents' clothing level in winter is given in Figure 4-14.

In summer, female respondents wore slightly more clothes than male respondents. The mean value of male's clothing level was 0.18clo and of females' 0.27clo. In winter, also more male respondents reported wearing light and medium clothing, and generally around 47% of respondents reported they wore heavy clothes in the home, no matter whether they were female or male.

Table4- 5: Summary of reported clothing level in summer (clo)

	Mean	Std.D	Min	Max
Male	0.179	0.090	0.00	0.36
Female	0.266	0.035	0.06	0.38

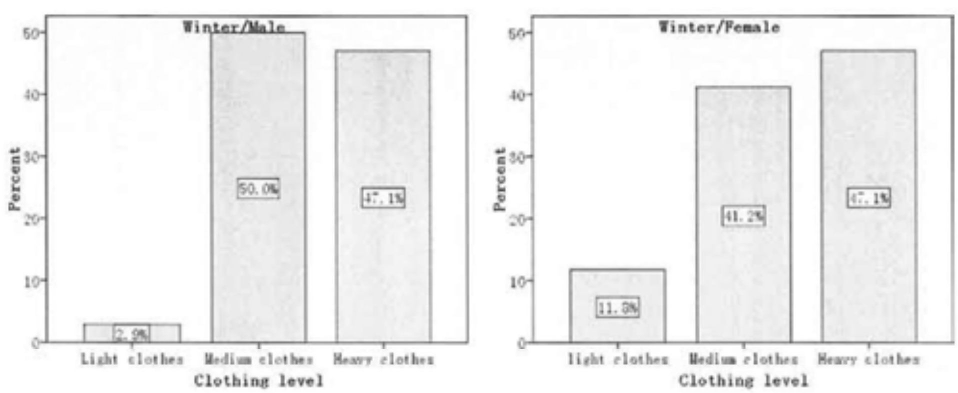


Figure4- 14: Clothing level reported by winter respondents

4.1.1.4.5 Attitude to choosing heating/cooling methods

Table 4-6 shows respondents' priority of driving factors for choosing heating/cooling methods. "Health" and "safety" were in the highest priority (more than 80% respondents voting the importance both in summer and winter), and "thermal efficiency", "economic efficiency" and "convenience" were also important driving factors for heating/cooling system selection.. In summer, many residents had recognized "sick building syndrome (SBS)"[39] (MD, CIH et al. 1997), and elders and children often suffered from it. Therefore, "health" became the first concern when residents decide to choose their cooling methods. In winter, probably because heaters could lead to some accidents at home, such as gas leaks, scalding and fire, "safety" was the first concern for deciding on heating methods.

Table4- 6: The priority of driving factors for choosing heating/cooling methods in winter and summer

Driving factor	Percentage of voting "high priority"		Priority ranking	
	Summer (n=309)	Winter (n=119)	Summer (n=309)	Winter (n=119)
Healthy	86.4%	84.9%	1	2
Safety	80.9%	89.0%	2	1
Convenience	62.5%	67.2%	5	5
Thermal efficiency	80.3%	75.7%	3	3
Economic efficiency	65.7%	70.6%	4	4

Note: "1" represents highest priority and "5" represents lowest priority.

The priority hierarchy indicates that local resident probably would sacrifice a little thermal comfort for more health and safety when necessary.

[39] "The term sick-building syndrome (SBS) refers to non-specific complaints, including upper-respiratory irritative symptoms, headaches, fatigue, and rash, which are usually associated with a particular building by their temporal pattern of occurrence and clustering among inhabitants or colleagues."

4.1.2 Investigation II

4.1.2.1 Sample size

The composition of respondents who participated in investigation II is given in Table 4-7. 513 sets of data (301 in summer and 212 in winter) were collected from 71 households in 'Free-Running" mode, that is, no air-conditioner/central heating system was in use during the investigation.

Both in summer and winter, there were more male than female respondents (53% male respondents in summer and 57% male respondents in winter); most respondents were young or middle aged, in good health (totally 60% respondents in the range 14~44 years old and 24% in the range 45~59 years old); and most of them had lived in HS&CW climatic zone for more than 12 years (around 90% both in summer and winter). These characteristics imply that all the respondents knew the local climatic conditions very well and had enough capability to express their thermal perception reliably.

Table4- 7: Sample summary for Investigation II

		Total (sample size:513)		Summer (total sample size:301)		Winter (total sample size:212)	
		Sample size	Percentage	Sample size	Percentage	Sample size	Percentage
Gender	**Male**	280	54.6%	159	52.8%	121	57.1%
	Female	233	45.4%	142	47.2%	91	42.9%
Age (years)	**14-44**	309	60.2%	208	69.1%	101	47.6%
	45-59	121	23.6%	77	25.6%	44	20.8%
	60-74	83	16.2%	16	5.3%	67	31.6%
Duration (years)	**4-12**	59	11.5%	36	12.0%	23	10.8%
	>=12	454	88.5%	265	88.0%	189	89.2%

4.1.2.2 Housing characteristics

In the investigation II, every household's apartment plan was recorded to study the indoor natural ventilation potential. Details of interior layout and location of doors and windows are shown in Appendix F. All of investigated apartments were located in city estates among surrounding building blocks. Because of compulsory design regulations for day lighting, and the linear layout of the housing units, most of the investigated apartments had three external walls, and all had at least two external walls. Therefore, the openings on those external walls make indoor natural ventilation possible, and some cases even had good potential to get cross ventilation.

Respecting the heating/cooling system, the overwhelming majority were equipped with individual air-conditioners and several housing units had central control air-conditioners. Likewise, they all owned a variety of heaters in winter. But, all the housing units were in the "Free-running" mode during investigation.

4.1.2.3 Clothing levels and metabolic rates

4.1.2.3.1 Clothing levels

Table 4-8 presents a summary of clothing level broken down by season and gender. There was very large clothing variation between seasons and slight variation between genders.

Occupants (mixed gender) wore clothing with average insulation value of "0.23clo" in summer and "2.03clo" in winter. If chair insulation was added, the total insulation value mean was 0.24clo in summer and 2.15clo in winter. Typical dressing in summer and winter for male and female is shown in Figure 4-15. Usually, at home, residents could dress whatever they liked, free from the dress-codes that can apply at the workplace. In summer, because of the extreme hot weather, males would like to be half-naked, and females typically wore thin and short pyjamas. In winter, because of little temperature difference between indoors and outdoors, occupants kept same clothing levels inside home and outdoors. The seasonal variation of clothing level in this study is much more significant compared with some previous studies (Bae and Chun 2009; Han, Yang et al. 2009; Rijal, Yoshida et al. 2010).

Table4- 8: Summary of clothing level in summer and winter (clo)

	Mixed				Male		Female	
	Clothing level		Clothing level+Chair insulation		Clothing level			
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Mean	0.23	2.03	0.24	2.15	0.20	2.02	0.27	2.05
Std.D	0.077	0.193	0.083	0.217	0.028	0.221	0.052	0.147
Min	0.03	1.30	0.03	1.40	0.03	1.30	0.19	1.80
Max	0.44	2.40	0.44	2.60	0.34	2.20	0.44	2.40

a b c d

Figure 4-15-a: male's dress in summer Figure 4-15-b: male's dress in winter
Figure 4-15-c: female's dress in summer Figure 4-15-d: female's dress in winter

Figure4- 15: Typical dress for male and female in summer and winter

Generally, male respondents' clothing level was slightly less than female respondents' both in summer and in winter. In summer, females had to cover their bodies and the minimum clothing level was about 0.19clo, approximately equalling to panties, bra, plus thin pyjamas. Meanwhile, males just needed underpants, with minimal clothing insulation of 0.03clo. In winter, females usually were thought to be more sensitive to cold and perhaps as a result they wore slightly more clothing. Actually, both male's and female's clothing was very heavy and close to each other (2.02clo from male and 2.05clo from female), but the female's maximum value and minimum value were both a little higher than the male's. Through independent-sample T test (Table 4-9, 4-10), it shows that the gender clothing difference in summer is statistically significant ($p<0.001$) but not in winter ($p=0.346/0.320$).

Table4- 9: Independent samples T test for clothing level in summer

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CLO	Equal variances assumed	31.917	.000	9.066	299	.000	.07129	.00786	.05581	.08676
	Equal variances not assumed			9.271	275.928	.000	.07129	.00769	.05615	.08642

Table4- 10: Independent samples T test for clothing level in winter

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CLO	Equal variances assumed	7.301	.007	.944	210	.346	.02521	.02671	-.02745	.07787
	Equal variances not assumed			.997	207.264	.320	.02521	.02529	-.02465	.07507

4.1.2.3.2 Metabolic rates

Respondents' metabolic rate is summarized in Table 4-11 broken down by season and gender. It shows little variation of metabolic rates existed between genders both in summer and winter. The average metabolic rates were around 1.2met to 1.3met, approximately corresponding to standing at rest or light office activities, as defined in the ASHRAE Handbook of Fundamentals(ASHRAE 2005).

Table4- 11: Summary of occupants' metabolic rate in summer and winter (met)

	Total		Summer		Winter	
	Summer	**Winter**	**Male**	**Female**	**Male**	**Female**
Mean	1.29	1.28	1.24	1.34	1.25	1.24
Std.D	0.454	0.198	0.427	0.478	0.180	0.199
Min	0.7	1.0	0.8	0.7	1.0	1.0
Max	3.0	1.9	3.0	3.0	1.6	1.9

In summer, the minimum metabolic rates came from sleeping or reclining in home. Occupants would like to have a siesta after lunch during the hottest period in the day. Maximum metabolic rate usually came from housework. In winter, minimum metabolic rate 1.0met usually came from quiet seating, and the maximum metabolic rate around 2.0met was for light housework or slowly walking. Although the average metabolic rates were similar, a seasonal variation was presented through the standard deviation (around 0.4met in summer while 0.2met in winter), which indicated that in summer occupants would conduct more varied activities, but in winter occupants were lazier and wanted more quiet activities.

4.2 PRESENTATION OF THERMAL ENVIRONMENTS

4.2.1 Measured indoor thermal variables

The field measurements were conducted in the 2007 summer and the winters through 2008 to 2010 in the Investigation II. As mentioned in Chapter 3 section 3.2.1.2.1, the climatic conditions in the selected measuring time could represent local climatic characteristics in terms of air temperature, relative humidity, air velocity and wind direction.

Table 4-12 presents a statistical summary of measured indoor thermal variables including air temperature, radiation temperature, relative humidity and air velocity by season. All the indoor thermal measurements were conducted in daytime because of security and permission constraints.

In summer, the air temperature mean was 31.3℃ with 1.66K standard deviation, and in winter mean value was 11.1℃ with standard deviation of 2.0K. Radiation temperature was very close to air temperature with 31.1℃ mean value in summer and 10.7℃ mean value in winter. Mean relative humidity was very close with each other in summer (64%) and winter (61%). Occasionally humidity would go up to 88% and decrease to 24% in winter. Indoor mean air velocity was quite low as 0.15m/s in summer and only 0.03m/s in winter.

Figure 4-16, 4-17, 4-18, 4-19 show the frequency distribution of measured indoor air temperature, radiation temperature and relative humidity; they are approximately Normal in form. However, the air velocity distribution was strongly skewed and the high frequency of "zero" value showed that the indoor air movement was often very slight. During summer increasing the air movement could have been advantageous for its cooling effect (Figure 4-14). High relative humidity value indicates these environments are quite damp, both in winter (maximum value of 81.8%) in summer (maximum value of 88.0%).

Table4- 12: Thermal measurement summary for Investigation II

	Summer (n=301)				Winter (n=212)			
	Air temperature (℃)	Radiation temperature (℃)	Relative humidity (%)	Air velocity (m/s)	Air temperature (℃)	Radiation temperature (℃)	Relative humidity (%)	Air velocity (m/s)
Mean	31.3	31.1	63.9	0.15	11.1	10.7	60.6	0.01
Std.D	1.66	1.89	7.78	0.23	2.00	2.18	13.04	0.019
Min	26.4	22.0	32.9	0.0	6.6	4.2	24.0	0.0
Max	36.1	37.4	81.8	1.8	16.0	23.2	88.0	0.10

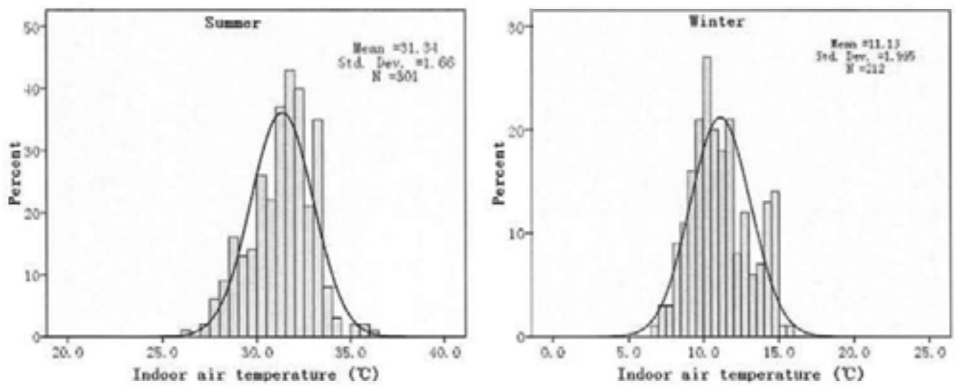


Figure4- 16: Air temperature distribution in summer and winter

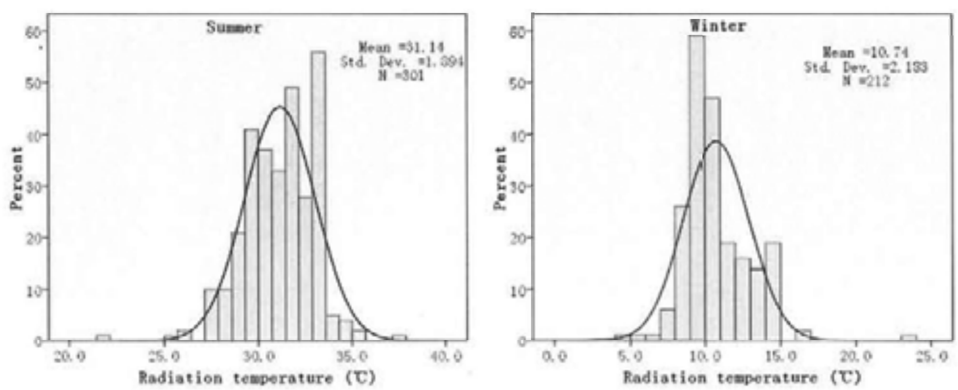


Figure4- 17: Radiation temperature distribution in summer and winter

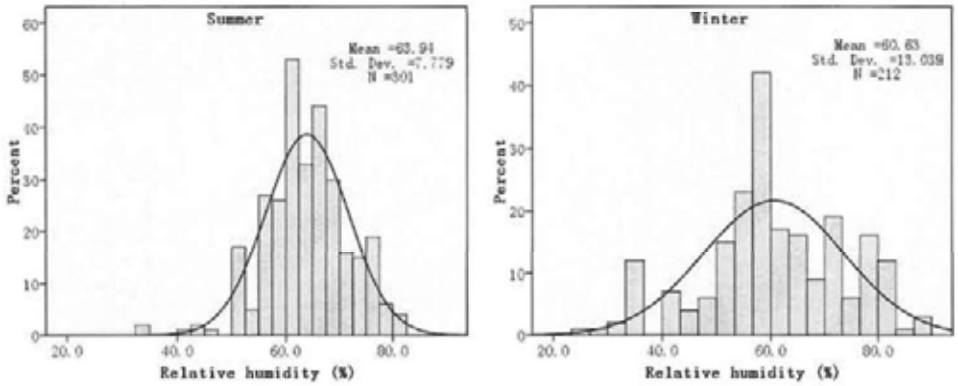


Figure4- 18: Relative humidity distribution in summer and winter

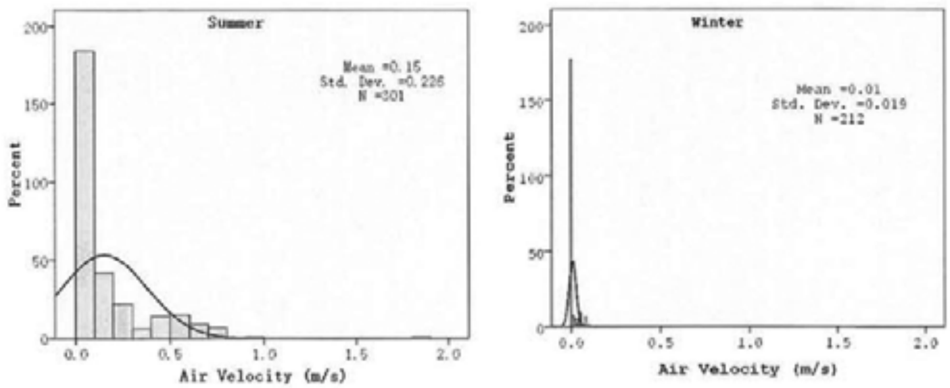


Figure4- 19: Air Velocity distribution in summer and winter

4.2.2 Environment comparisons between indoors, outdoors and observatory

Table 4-13 gives the Paired-sample T test and bivariate-correlation testing of indoor and outdoor environments including measured air temperature, relative humidity and air velocity. The outdoor mean air temperature is only 2.0K higher than the indoor in summer, while in winter the difference is only 1.2K; the relative humidity difference in summer is 5.9% and 1.7% in winter; the air velocity is very low both indoors and outdoors and the difference between them is negligible.

Table4- 13: Paired-sample T test and bivariate-correlation testing between indoor and outdoor (balcony data)

Period	Summer			Winter		
	Air temperature (℃/K)	Relative humidity (%)	Air velocity (m/s)	Air temperature (℃/K)	Relative humidity (%)	Air velocity (m/s)
Simple size	280	280	280	206	206	206
Mean_Indoor	31.4	64.5	0.12	11.1	60.9	0.02
Mean_Outdoor	33.4	58.7	0.22	9.9	59.2	0.11
Difference between indoor and outdoor	-2.0	5.9	-0.1	1.2	1.7	-0.09
Sig.(2-tailed)	0.000	0.000	0.000	0.000	0.006	0.004
Pearson *r*	0.494	0.546	0.071	0.637	0.827	0.487
Correlation Sig.	0.000	0.000	0.239	0.000	0.000	0.000

The comparisons of measured indoor and outdoor thermal variables show that in the naturally ventilated buildings, with the exception of air speed, indoor thermal environments were correlated with outdoor thermal environments, and the mean differences between them were slight.

Meanwhile, comparisons of climate data between indoors, outdoors and local observatory (night time data through 9PM to 5AM were eliminated) were carried out as showed in Table 4-14. It was found that measured indoor air temperature was a little lower than outdoors and observatory data in summer, while it was much higher in winter. The differences in relative humidity were in the opposite direction, as would be expected. Indoor air speed and outdoor speed near the building were much lower than observatory's values both in summer and winter, which indicated the considerable blocking effect of the buildings in the urban housing estates. Although most investigated apartments had enough external opening, and observatory's velocity value was higher, at 2.0m/s, the indoor air was almost still, and the outdoor air movement also low.

Table4- 14: Comparison of TA, RH, VEL within indoor, outdoors and observatory

Period	Summer			Winter		
	Indoors	outdoors	Observatory	indoors	outdoors	Observatory
Mean air temperature (℃)	31.3	33.4	33.2	11.1	9.9	7.0
TA_Standard Dev.	1.66	2.51	3.08	2.00	3.17	3.62
Mean relative humidity (%)	63.9	58.7	55.1	60.6	59.2	79.2
RH_Standard Dev.	7.78	8.06	11.17	13.04	15.14	15.35
Mean air velocity (m/s)	0.15	0.22	1.88	0.01	0.11	2.0
Vel_Standard Dev.	0.23	0.20	0.75	0.019	0.31	1.13

4.2.3 Indoor thermal indices

Table 4-15 presents a statistical summary of indoor thermal indices compromising operative temperature (T_{op}), effective temperature (ET), standard effective temperature (SET) and predicted mean vote (PMV) broken down by season.

Operative temperature is important when comparing the survey results to ASHRAE Standard 55, since the cool and warm boundary of the comfort zone are prescribed in terms of operative temperature. The indoor mean operative temperature measured in summer was high at 31.3℃, with standard deviation 1.7K, and the mean operative temperature in winter was low at 10.9℃ with standard deviation 2.0K. The mean effective temperature (ET*) in summer was even higher than 32.2℃ with standard deviation 1.8K, but the mean value was low at 10.7℃ with standard deviation 1.7K in winter. The standard effective temperature in summer was 29.5℃ with the standard deviation of 2.4K and mean value was 23.5℃ with the standard deviation of 2.6K in winter. The average predicted mean vote in summer was "1.93" and average value was "-0.57" in winter. These PMV values indicated that many people would experience heat discomfort in summer, and the thermal environment in winter was just slightly cool (PMV takes into account occupants' clothing insulation and metabolic rate.).

Table4- 15: Summary of calculated thermal indices in summer and winter

	Summer (n=301)				Winter (n=212)			
	T_{op} (℃)	ET^*(℃)	SET(℃)	PMV	T_{op} (℃)	ET^*(℃)	SET(℃)	PMV
Mean	31.3	32.2	29.5	1.93	10.9	10.7	23.5	-0.57
Std.D	1.7	1.8	2.4	0.75	2.0	1.7	2.6	0.5
Min	26.1	25.9	22.7	-0.9	6.6	6.6	17.9	-2.0
Max	36.5	37.5	36.2	3.7	18.3	18.3	31.4	0.7

Exploratory analysis aided by SPSS package indicated that these four thermal indices are in approximately Normal distribution as shown in Figure 4-20, 4-21, 4-22, 4-23.

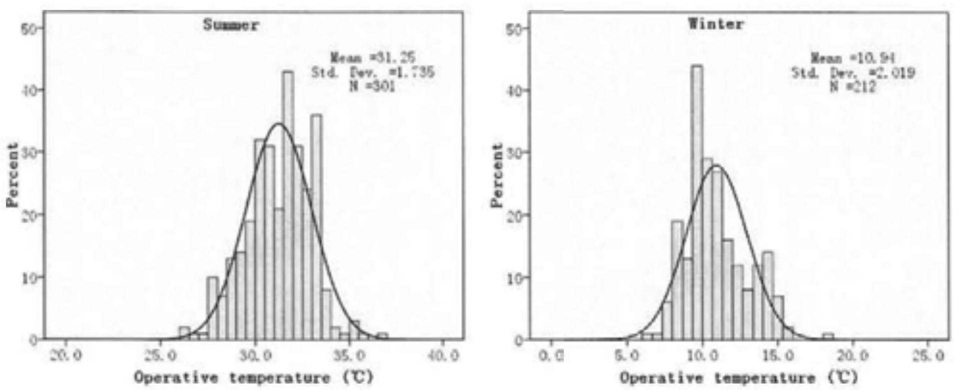


Figure4- 20: Frequency distributions of operative temperature in summer and winter

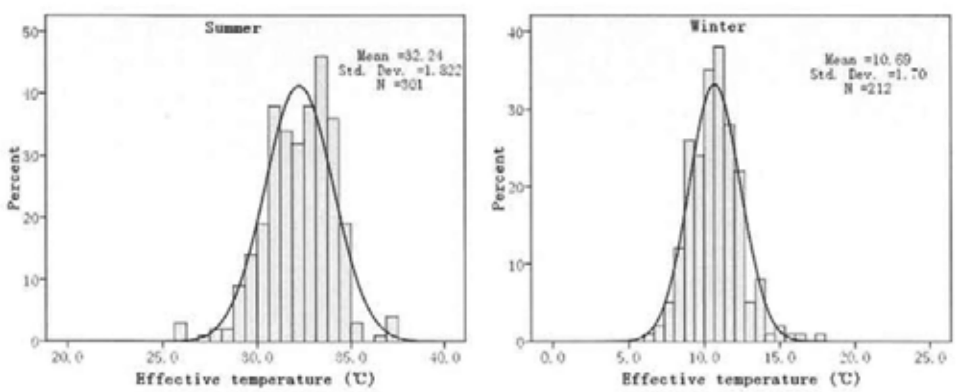


Figure4- 21: Frequency distributions of effective temperature in summer and winter

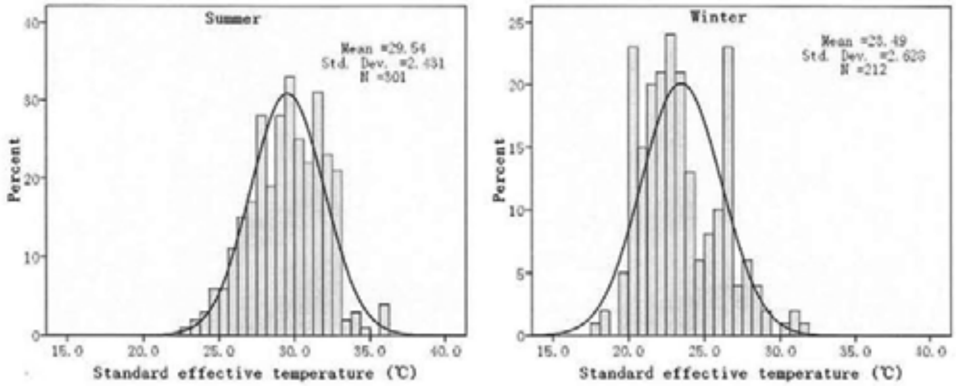


Figure4- 22: Frequency distributions of standard effective temperature in summer and winter

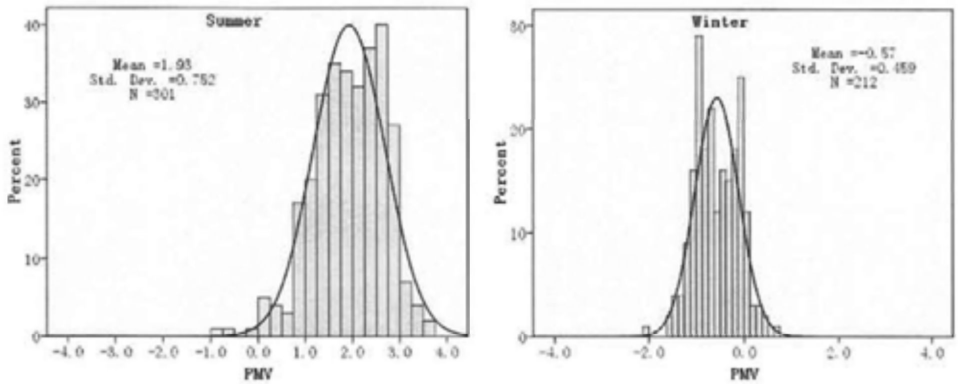


Figure4- 23: Frequency distributions of predicted mean vote in summer and winter

4.2.4 Comparisons with the conventional thermal comfort zone

Each measured thermal point in this investigation was plotted on a psychometric chart of relative humidity and operative temperature as shown in Figure 4-24. In this chart, the blue zone represents the acceptable thermal boundary for occupants with 1.0clo clothing level, and red zone represents acceptable thermal boundary for occupants with 0.5clo clothing level (ASHRAE 2010). Obviously, the overwhelming majority of observations fell outside the boundaries of acceptable thermal conditions as defined by ASHRAE. Therefore, the investigated typical climatic conditions in summer and winter in Wuhan definitely were uncomfortable according conventional thermal comfort standards.

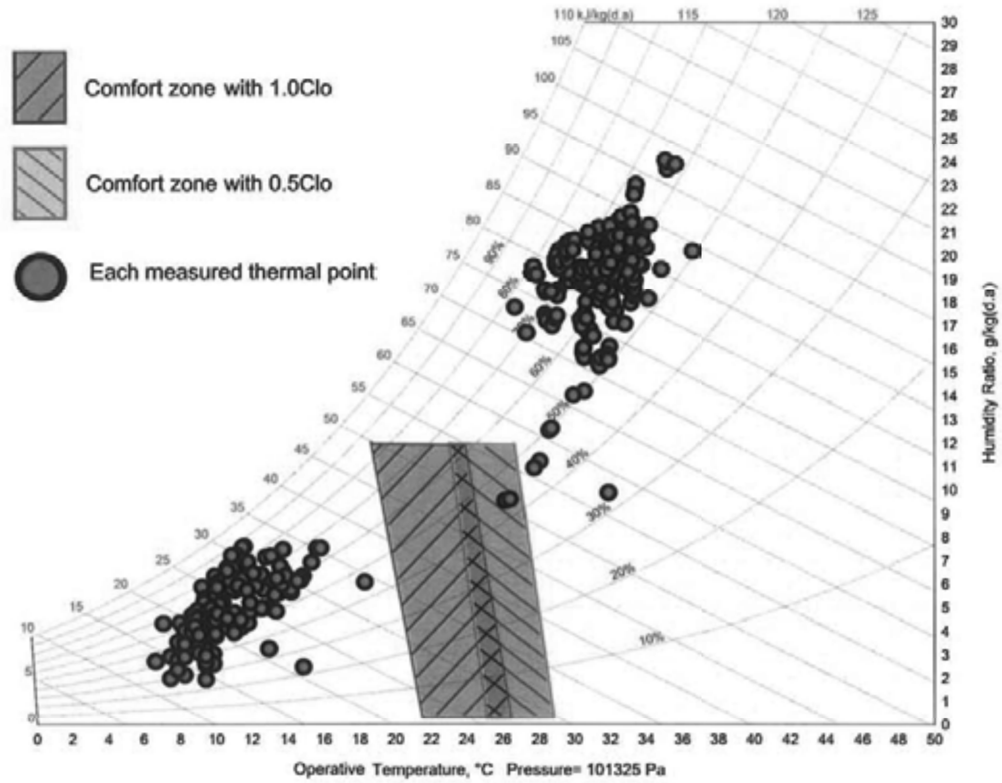


Figure4- 24: Measured indoor thermal environments scattered on the psychometric chart

4.3 SUBJECTIVE THERMAL PERCEPTION

In this study, there were four standard questions to investigate occupants' thermal perception as described in the section 3.2.1.4. They were thermal sensation (ASH), thermal comfort (COMF), thermal preference (MCI) and thermal acceptability (TSA). Additionally, humidity sensation (HUS) and air movement sensation (AMS) also were acquired. Table 4-16 contains a statistical summary of the occupants' subjective thermal perception votes both in summer and winter.

Table4- 16: Summary of occupants' thermal perception variables by season

	Summer (n=301)						Winter (n=212)					
	ASH	COMF	MCI	TSA	HUS	AMS	ASH	COMF	MCI	TSA	HUS	AMS
Mean	0.85	0.75	2.79	0.39	2.50	2.01	-0.84	0.62	1.36	1.53	2.91	3.00
Std. dev.	0.89	0.66	0.43	0.49	0.77	.70	0.92	0.55	0.48	1.24	0.67	0.37
Min	-1.0	0.0	1.0	0.0	1.0	1.0	-3.0	0.0	0.0	0.0	2.0	1.0
Max	3.0	3.0	3.0	2.0	5.0	3.0	2.0	2.0	3.0	3.0	5.0	4.0

4.3.1 Thermal sensation (ASH)

Figure 4-25 shows the percentage distribution of integer thermal sensation votes both in summer and winter. From Figure 4-25 and Table 4-16, it is seen that the mean thermal sensation vote in summer centred on 0.85, and the commonest vote was "neutral" (36% occupants voting "0") and "slightly warm" (42% occupants voting "1"); while in winter, the mean thermal sensation was "-0.84", and similarly most occupants voted "neutral" (34% voting "0") and "slightly cool" (43% occupants voting "-1"). Although most observed thermal points were outside the acceptable boundary according to the ASHRAE standard (as shown in Figure 4-24), occupants clearly indicated their thermal sensation around the central three categories.

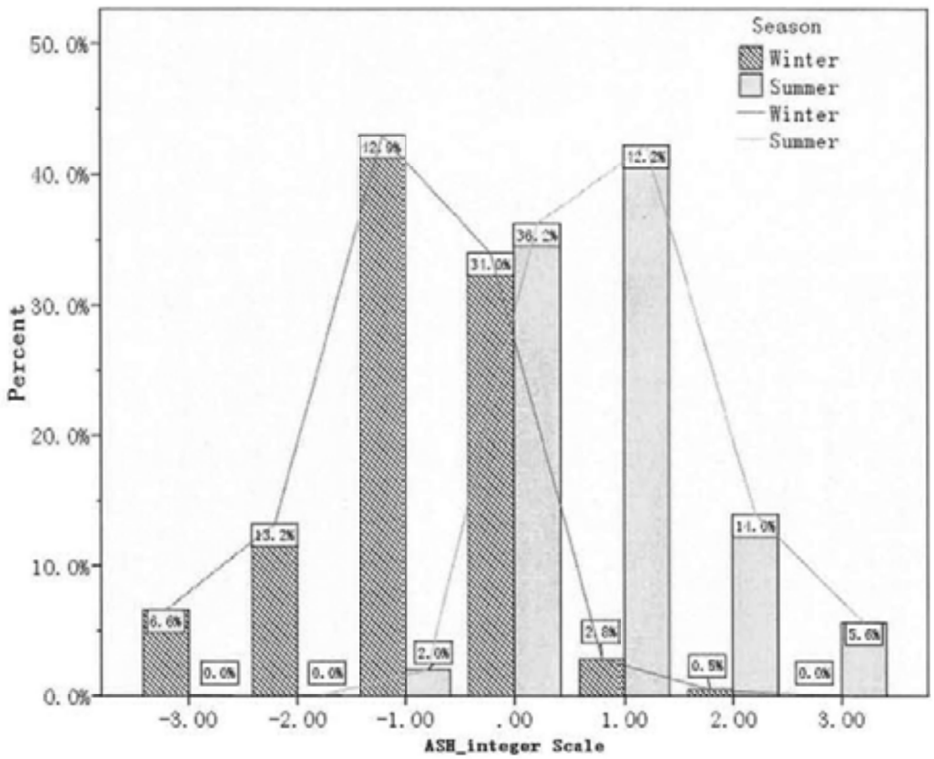


Figure4- 25: Distribution of integer thermal sensation votes on the ASHRAE scale

Following this, an analysis of thermal sensation was carried out with respect to indoor warmth in terms of: a) operative temperature (TOP), b) standard effective temperature (SET) and c) predicted mean vote (PMV). These indices were binned into one-degree steps and linear regression models were fitted according to the following format (Equation 4-1) (de Dear, Brager et al. 1997). SPSS software package was used in the binning process and regression models generation. The purpose of binning data was to minimize the effects from varied sample size in each group, and each studying variable bin was weighted for regression by the number of observation. In this study, similar regression process was also applied the analysis for other thermal perception variables compromising thermal comfort, thermal preference, thermal acceptance, humidity sensation and velocity sensation.

Mean thermal sensation= a*(binned index value)+b   (4-1)

a, b: coefficient and constant

After fitting linear regression equation, thermal index ranges ensuring ASH mean value within "-1~1" could be draw, which corresponds to 75% thermal satisfaction approximately (according to the PPD model). The neutral point corresponding to ASH value equalling to "0" was also calculated.

4.3.1.1 Dependence of thermal sensation on indoor operative temperature

All the linear regression models of thermal sensation on operative temperature achieved statistical significance ($p<0.05$, the same blow) both in summer, winter and for the whole year as shown in Figure 4-26 and Table 4-17. The gradient of the linear regression (value of "b") indicates how much the thermal sensation ("ASH_mean") changes with each operative temperature unit ("TOP (binned)"). Undoubtedly, occupants' thermal sensitivity varied greatly between seasons. Coefficient value in summer was "0.04", in winter was "0.1" and in the whole year was "0.083". Although occupants were more sensitive to thermal environment in winter than in summer, all of them were less sensitive comparing with respondents contributing to others' research conducted in naturally ventilated buildings. (The results were quoted in Table 2-2 in section 2.2.2 and most of those coefficients centred on "0.2" to "0.5"). It described local residents' strong thermal adaptability under these hot-summer & cold-winter climatic conditions.

Table4- 17: Summary of thermal sensation votes responding on indoor operative temperature by season

	Sample size (n)	TOP range (℃)	Regression equation	R^2	Range fulfilling -1<=ASH<=1 (℃)
Whole year	513	7~37	Y=0.083*X-1.75	0.961	9.0~33.1
Summer	301	26~37	Y=0.037*X-0.30	0.189	-18.9~35.1
Winter	212	7~18	Y=0.093*X-1.86	0.501	9.2~30.8

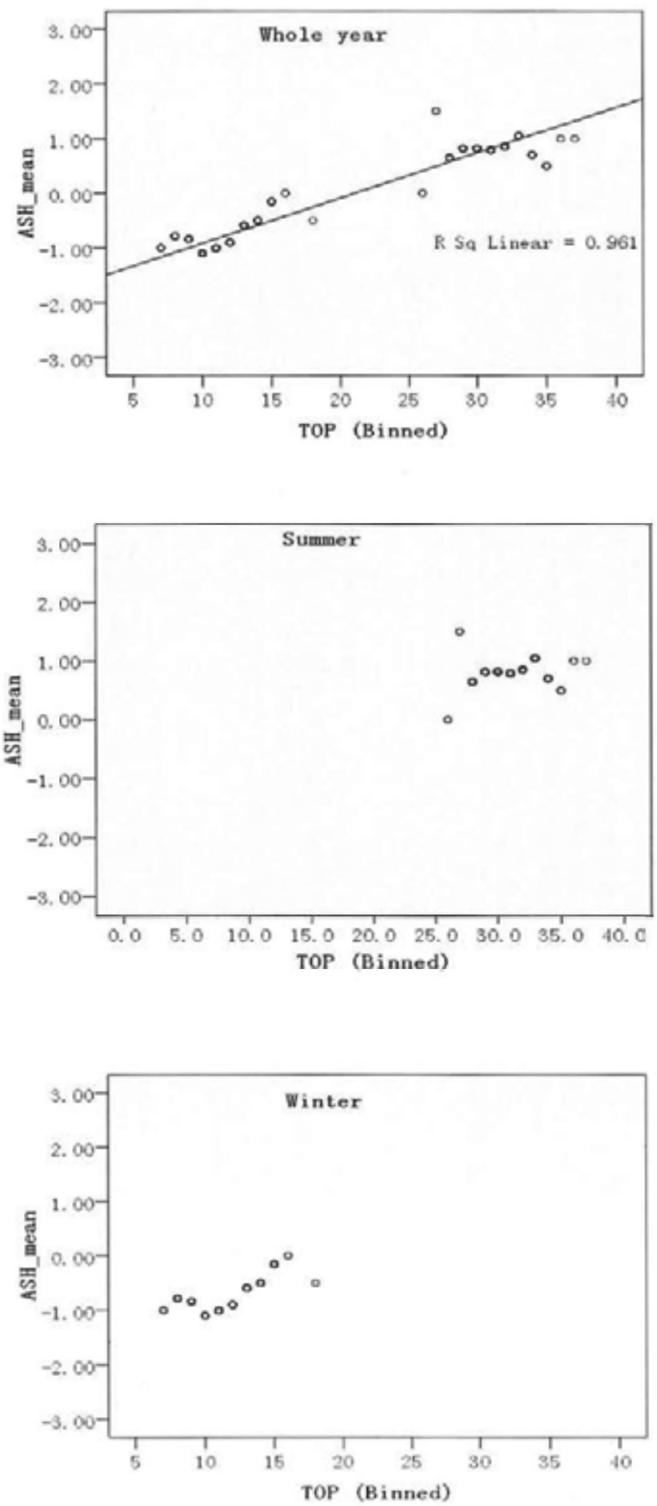


Figure4- 26: Scatted points of mean thermal sensation votes against binned indoor operative temperature

However, because no spring and autumn data were collected in this study, all the observation points in this study skewed to either hot or cold condition, which made the linear regression analysis in respective seasons varied. Based on these three simple linear regression models, it is found that the model drawn from winter was not statistically different from the model drawn from whole year data in terms of coefficient and intercept value because their values were within two standard errors of each other (Table 4-18). Meanwhile, temperature range fulfilling "-1<ASH<1" (-18.9℃~35.1℃) and neutral temperature (-8.1℃), which were calculated from summer model also looks unreasonable. Therefore, only whole year regression model of "Y=0.083*X-1.75" was accepted in this study to represent the dependence of "ASH" on "TOP".

Table4- 18: 95% confidence interval of model coefficients drawn from winter data

	Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-1.863	.071		-26.075	.000	-2.004	-1.722
	TOP (Binned)	.093	.006	.708	14.522	.000	.080	.105

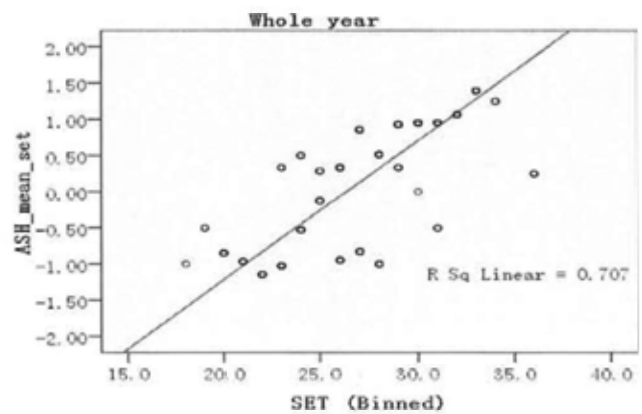
4.3.1.2 Dependence of thermal sensation on indoor standard effective temperature

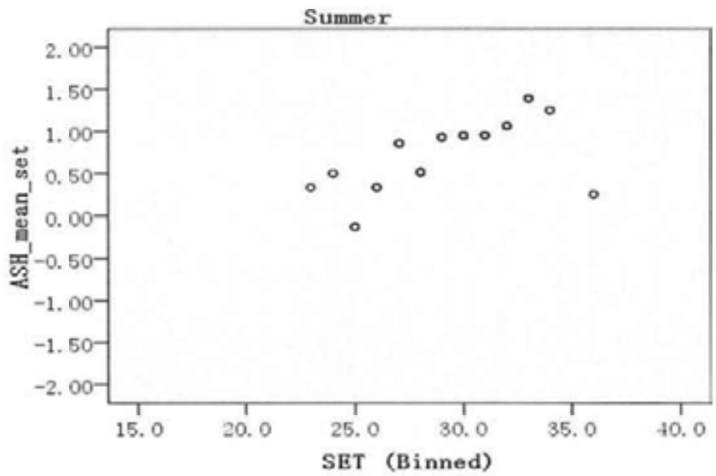
All the linear regressions models of thermal sensation votes against standard effective temperature also achieved statistical significance at the 95% confidence level in summer, winter and the whole year as shown in Table 4-19 and Figure 4-27.

As an integrated thermal index, standard effective temperature has taken into account the effects of physical variables as well as personal clothes and metabolic rates. It is expected that SET would be a better indicator to predict occupants' thermal sensation. In this study, the thermal sensation against SET in summer was more sensitive (coefficient value of "0.094") than the thermal sensation against SET in winter (coefficient value of "0.043"), and the whole year's value of "0.192" showed its consistence with the international data results (coefficient value of "0.154") in naturally ventilated buildings (de Dear, Brager et al. 1997). But if it was compared with original comfort categories defined based on SET (gradient value of "0.284") (Gagge, Stolwijk et al. 1971), this integrated thermal index SET still could not fully explain occupants' "insensitive" thermal sensation in the "free" building environments. More details of this comparison will be unfolded in the discussion chapter section 5.2.1.1.

Table4- 19: Summary of thermal sensation votes responding on standard effective temperature by season

	Sample size (n)	SET range (℃)	Regression equation	R^2	Range fulfilling -1<=ASH<=1 (℃)
Whole year	513	18~36	Y=0.192*X-5.05	0.707	21.1~31.5
Summer	301	23~36	Y=0.094*X-1.93	0.532	9.9~31.2
Winter	212	18~31	Y=0.043*X-1.86	0.124	20.0~66.5





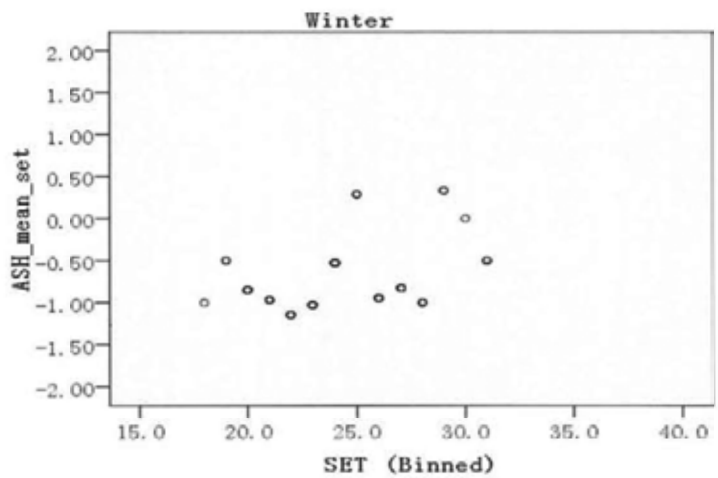


Figure4- 27: Scattered points of mean thermal sensation votes against binned standard effective temperature

4.3.1.3 Dependence of thermal sensation on predicted mean vote

Regressions of thermal sensation against indoor Predict Mean Vote (PMV) are showed in Table 4-20 and Figure 4-28. All the regression models drawn from summer, winter and whole year data achieved statistical significance at the 95% confidence level.

Since the ASHRAE thermal sensation scale and PMV address same thermal scale, the expected gradient of regression equation should equal to "1". However, variation existed not only between "ASH" and "PMV" but also between seasons. Local residents had higher thermal sensitivity in winter (gradient value of "0.275") compared with in summer (gradient value of "0.174"). For the whole year, the coefficient of "ASH" against "PMV" jumped to "0.569", which meant the PMV could only explain approximately one half of the residents' thermal adaptability in the naturally ventilation buildings. This result also shows its consistency with international data results (gradient value of "0.62") as shown in Figure 5-2 (de Dear, Brager et al. 1997). In Chapter 5, more discussion about comparison of this study with other researchers' work will be carried out.

Table4- 20: Summary of thermal sensation votes responding on predicted mean votes by season

	Sample size (n)	PMV range	Regression equation	95% Confidence Interval for Coefficient	R^2	Range fulfilling -1<=ASH<=1 (℃)	Neutral point (ASH=0) (℃)
Whole year	513	-2~4	Y=0.569*X-0.363	(0.550, 0.589)	0.866	-1.12~2.40	0.64
Summer	301	-1~4	Y=0.174*X+0.514	(0.152, 0.159)	0.448	-8.70~2.79	-2.95
Winter	212	-2~0.5	Y=0.275*X-0.688	(0.239, 0.310)	0.520	-1.13~6.14	2.50

Additionally, the neutral points were also calculated to verify the discrepancy between observed thermal sensation (ASH) and predicted thermal sensation (PMV). It is interesting that, for the whole year data, neutral sensation (ASH=0) was achieved when body got slightly positive thermal load with PMV value of "0.64".

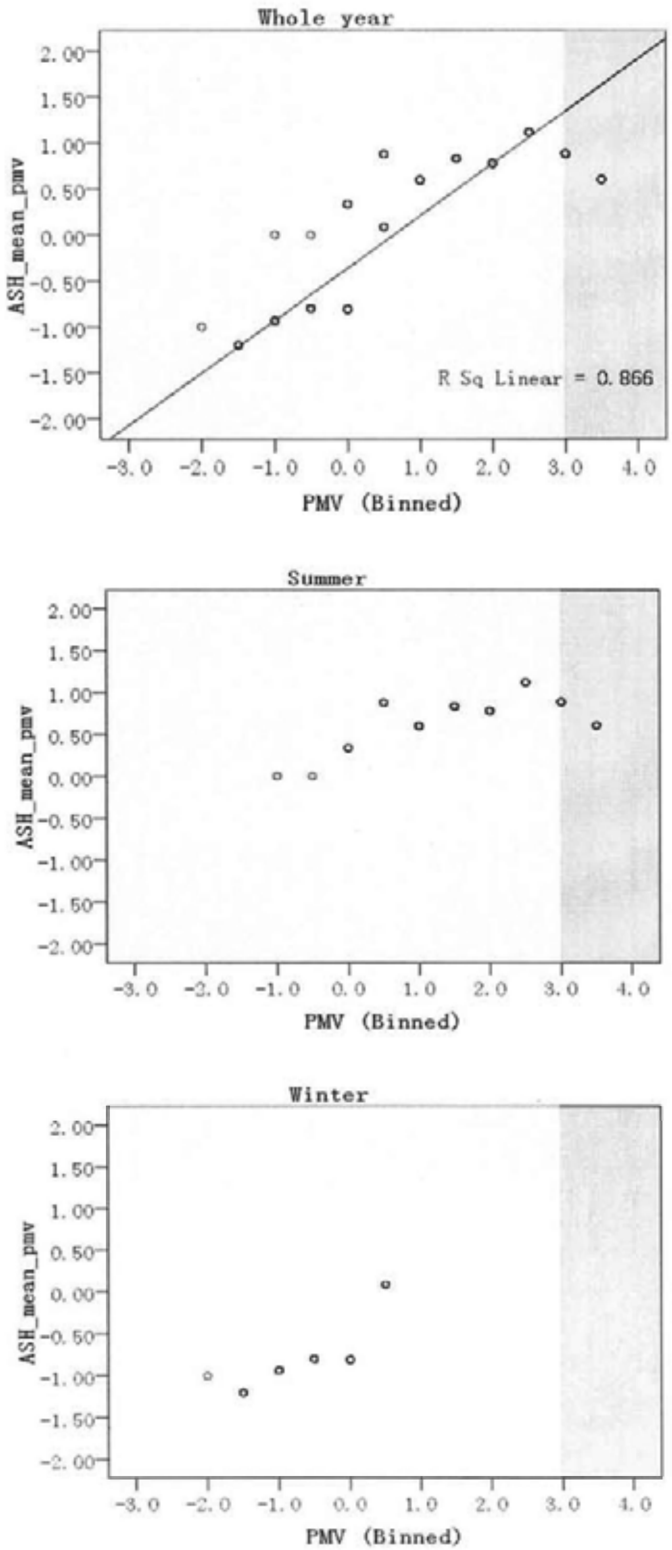


Figure4- 28: Scatted points of mean thermal sensation votes against binned predicted mean votes

4.3.2 Thermal comfort (COMF)

The direct thermal comfort question attempted to get a broader picture of the subjective thermal state of occupants by using a four-point comfort scale to distinguish overall comfort satisfaction from thermal sensation.

The statistical summary of thermal comfort votes indicated that the mean general comfort was between "comfortable" and "slightly uncomfortable" both in summer with mean value of "0.75" and winter with mean value of "0.5" (Table 4-16). The percent distribution of integer thermal comfort votes (Figure 4-29) also showed that more than ninety percent occupants (97% in winter and 91% in summer) voted these two options which means that local residents generally felt slight or no discomfort during the investigated periods.

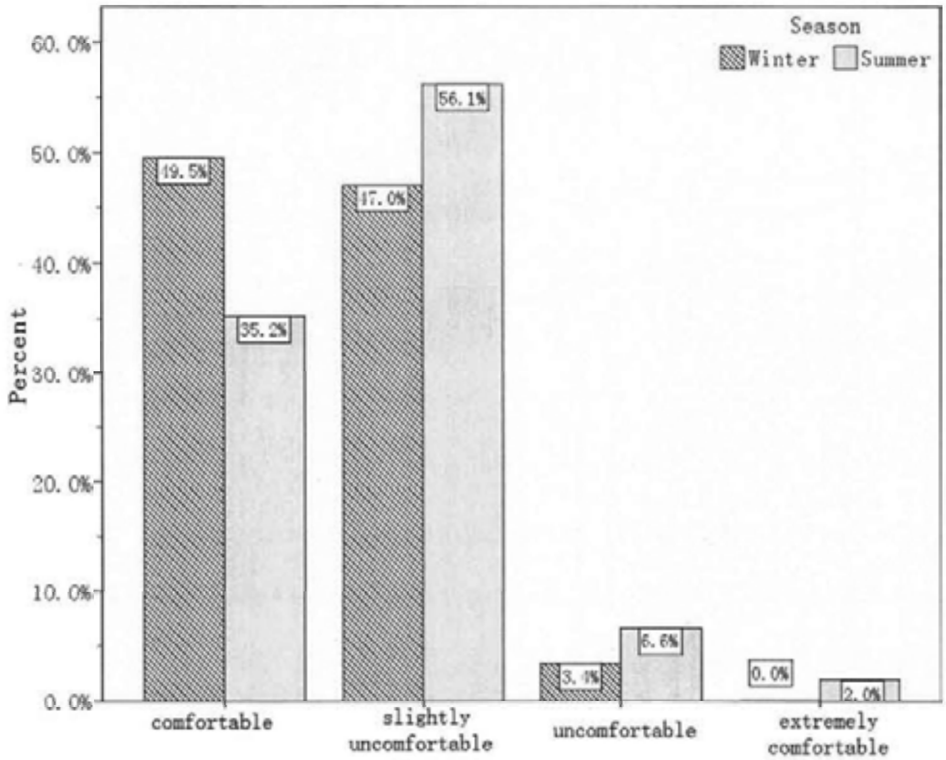


Figure4- 29: Percent distribution of integer thermal comfort votes in summer and winter

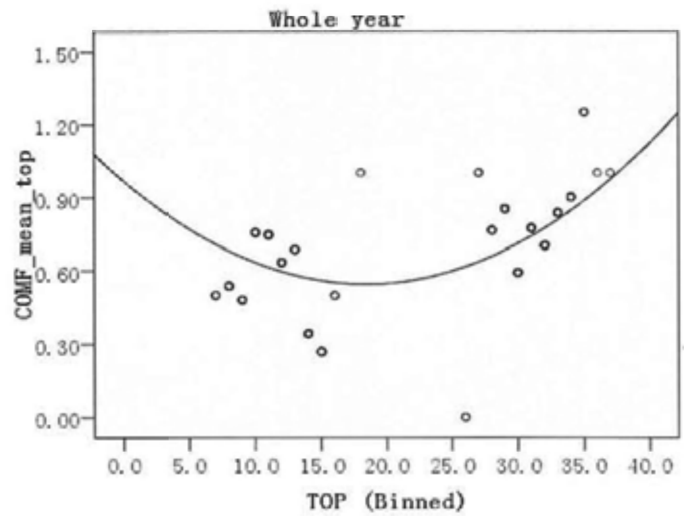
4.3.2.1 Dependence of thermal comfort on thermal indices

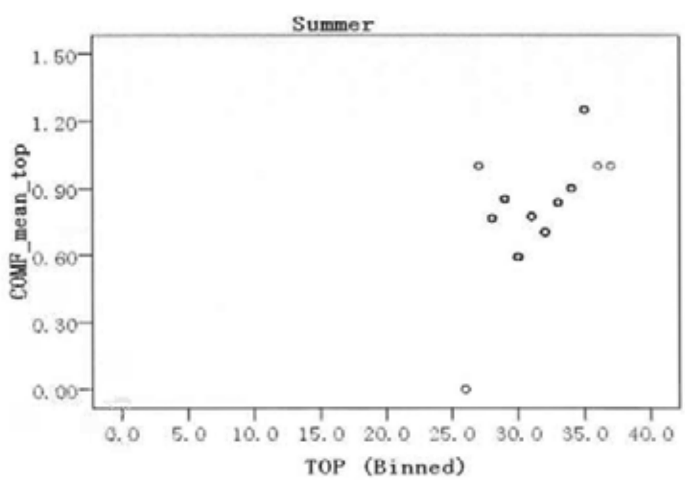
As for thermal sensation analysis, scattered mean thermal comfort votes against operative temperature, effective temperature, and predicted mean vote are presented in the Figure 4-30, 4-31 and Figure 4-32 respectively.

The binned values of COMF lay mostly between 0.3 and 1.2, regardless what the operative temperature, standard effective temperature or predicted mean vote were. Linear regression models drawn from both summer and winter data were statistically significant (Table 4-21, 4-22, 4-23). However, linear regression models are incapable of predicting a maximum value of comfort on the thermal index, therefore polynomial regression models, which were drawn from whole year data, were employed to estimate what occupants would feel most comfortable (approximate COMF vote of "0.6") when the operative temperature is 23.0℃, standard effective temperature is 26℃, and predicted mean vote is 0.09.

Table4- 21: Summary of thermal comfort votes responding on operative temperature by season

	Sample size (n)	TOP range (℃)	Regression equation	R^2	Most comfortable TOP (℃)
Whole year	513	7~37	$Y=0.00124*X^2-0.046X+0.967$	0.275	23.0
Summer	301	26~37	$Y=0.032*X-0.247$	0.195	
Winter	212	7~18	$Y=-0.0200*X+0.839$	0.066	





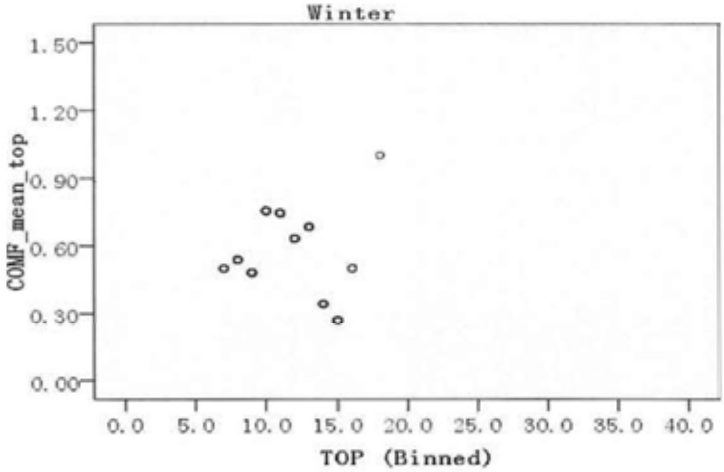
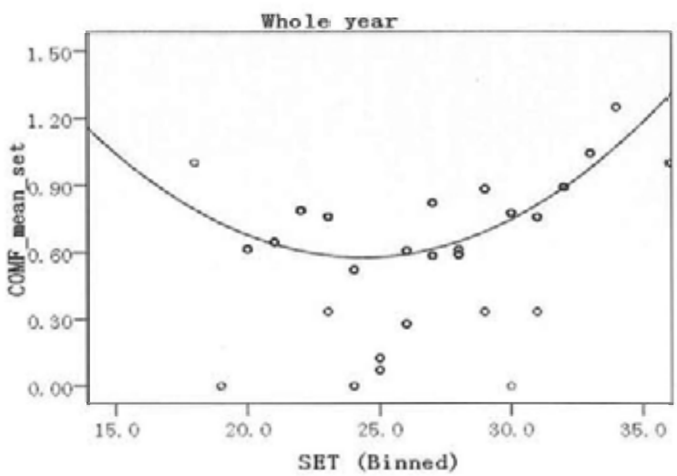


Figure4- 30: Scatted points of mean thermal comfort votes against binned operative temperature by season

Table4- 22: Summary of thermal comfort votes responding on standard effective temperature by season

	Sample size (n)	SET range (℃)	Regression equation	R^2	Most comfortable SET (℃)
Whole year	513	18~36	$Y=0.00535*X^2-0.26X+3.747$	0.358	26.0
Summer	301	23~36	$Y=0.074*X-1.431$	0.143	
Winter	212	18~31	$Y=-0.024*X+1.177$	0.621	



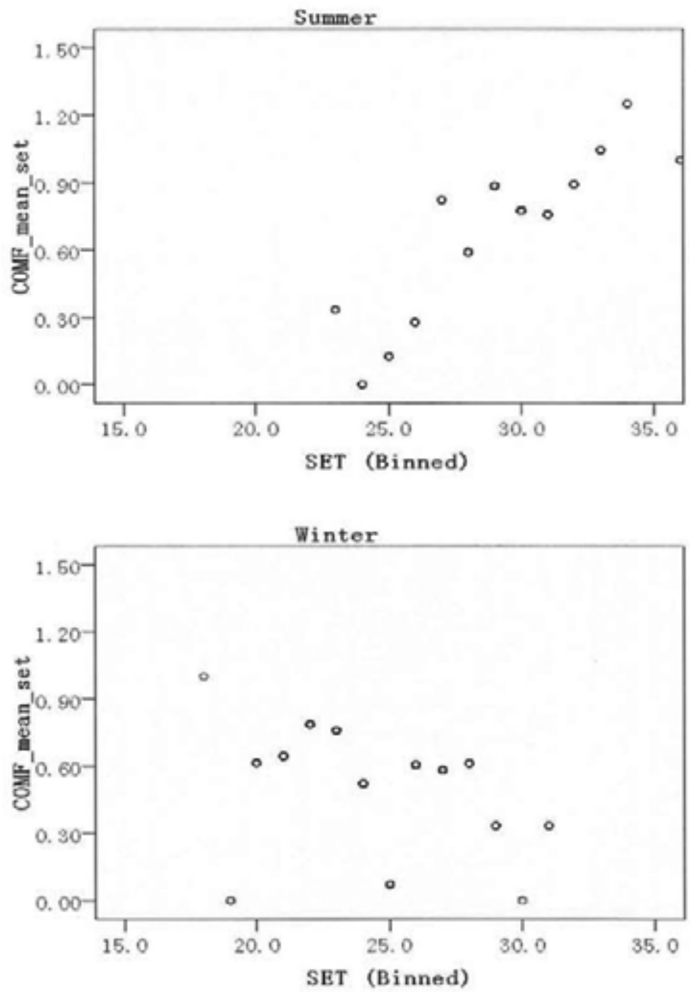


Figure4- 31: Scatted points of mean thermal comfort votes against binned standard effective temperature by season

Table4- 23: Summary of thermal comfort votes responding on predicted mean vote by season

	Sample size (n)	PMV range	Regression equation	R^2	Most comfortable PMV
Whole year	513	-2~4	$Y=0.041*X^2-0.007X+0.591$	0.62	0.085
Summer	301	-1~4	$Y=0.157*X+0.45$	0.513	
Winter	212	-2~0.5	$Y=-0.12*X+0.551$	0.708	

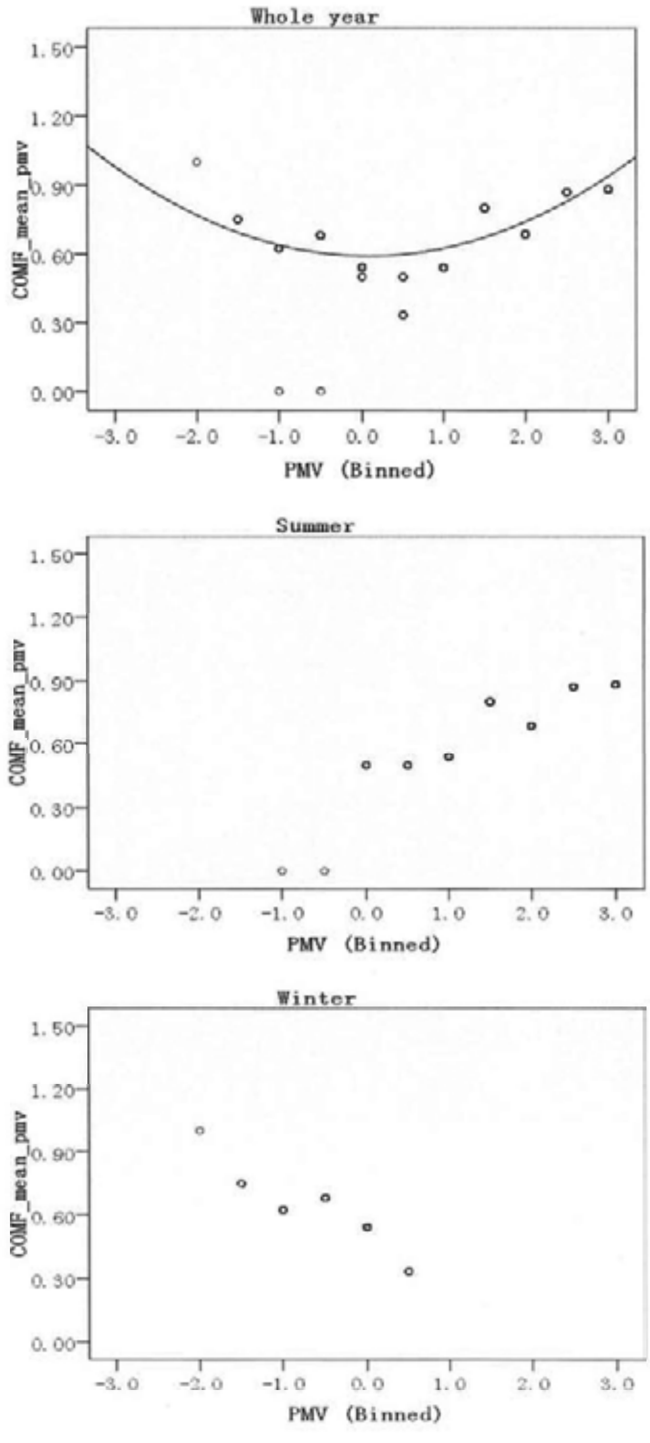


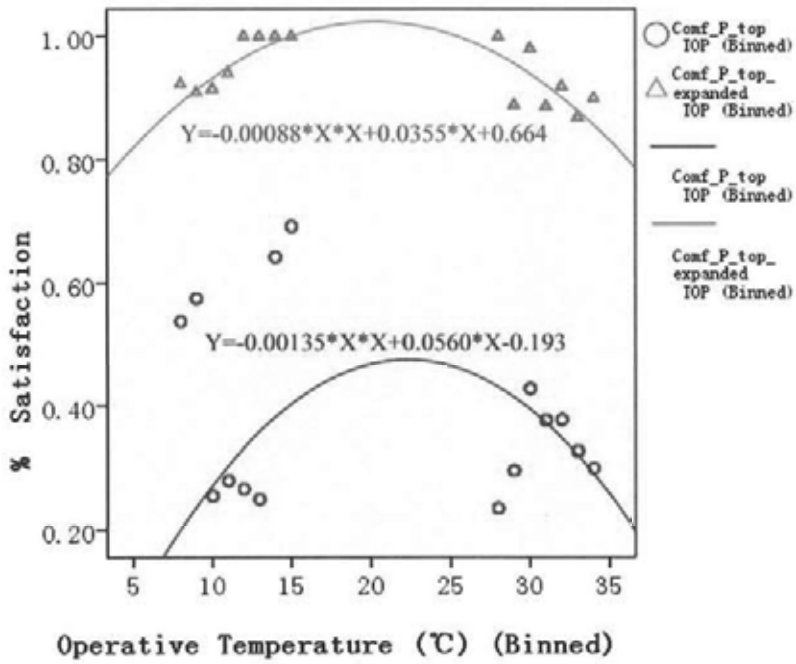
Figure4- 32: Scatted points of mean thermal comfort votes against binned predicted mean vote by season

4.3.2.2 Thermal comfort percentage against operative temperature

Furthermore, four answers of "comfortable, slightly warm/cool uncomfortable, hot/cold uncomfortable and extremely hot/cold uncomfortable" were recorded into binary comfort variable coding of "Comfort Percentage" or "Expanded Comfort Percentage" in different ways (Table 4-24). "Comfort Percentage" is to define "comfortable=1" corresponding to the vote of "comfortable", while "uncomfortable=0" corresponding to votes of "slightly uncomfortable", "uncomfortable" and "extremely uncomfortable". The other way is to define "comfortable=1" corresponding to votes of "comfortable" and "slightly uncomfortable", while "uncomfortable=0" corresponding to votes of "uncomfortable" and "extremely uncomfortable". This "Expanded Comfort Percentage" drawn through the second way was employed by Brager to investigated occupants acceptability based on the general comfort scale (Brager, Fountain et al. 1993). By addressing these two ways, the dependence of comfort percentage against on operative temperature were plotted in Figure 4-33.

Table4- 24: Coding for "Comfort Percentage" and "Expanded Comfort Percentage"

	1=comfortable	**0=uncomfortable**
Comfort Percentage	"Comfortable"	"Slightly uncomfortable" "Uncomfortable" "Extremely uncomfortable"
Expanded Comfort Percentage	"Comfortable" "Slightly uncomfortable"	"Uncomfortable" "Extremely uncomfortable"



(circle point: Comfort Percentage, triangle point: Expanded Comfort Percentage)

Figure4- 33: Mean comfort percentage against on operative temperature

It is found that, if vote of "slightly uncomfortable" was defined as "comfortable=1", measured operative temperature could make around 90% respondents comfortable. However, if votes of "slightly uncomfortable" was defined as "uncomfortable=0", measured operative temperature could only make around 40% respondents comfortable, no mater what temperature was. The results indicated that comfort percentage greatly depended on the definition of "comfort" but slightly depended on real thermal stimulus. Meanwhile, there was no chance to calculate the 80% comfort satisfaction based on these data because of their gathering around value of "0.9" or "0.4".

4.3.3 Thermal preference (MCI)

4.3.3.1 Dependence of thermal preference on thermal indices

Thermal preference indicates occupants' intention of changing or keeping current thermal environments. The votes of "warmer" (voting value of "1") and "cooler" (voting value of "3") mean that occupants are not satisfied with corresponding thermal environments and therefore they prefer changing to warmer/cooler conditions; while "no change" (voting value of "2") means that occupants are satisfied with corresponding thermal environments they are exposed to.

Drawing linear regression models, there were statistically significant regression results could be found between thermal preference votes against operative temperature, standard effective temperature and predicted mean vote from the whole year data[40] (Table 4-25 and Figure 4-34, 4-35, 4-46). Based on these models, MCI would get "2" value when TOP was 19.9℃, SET was 25.7℃ and PMV was 0.47. This result was consistent with the analysis of dependence of "ASH" against "PMV", which repeated that neutral sensation happed when thermal load on human body was slightly positive.

Table4- 25: Summary of thermal preference votes responding on operative temperature by season

	Sample size (n)	TOP/SET/PMV range (℃)	Regression equation	R^2	Preferred neutral thermal indices (℃)
Whole year	513	7~37	Y=0.069*X+0.625	0.959	19.9
Whole year	513	18~36	Y=0.15*X-1.856	0.666	25.7
Whole year	513	-2~4	Y=0.462*X+1.782	0.818	0.47

[40] In this scattered diagram, points whose frequency is less than 8 are eliminated with the aid of Figure 4-20, 4-21, 4-23.

Meanwhile, the scattered points of thermal preference votes against these thermal indices in respective season showed that the mean MCI value changed little as TOP, SET and PMV changed within season. It meant that majority of occupants wanted “cooler” in summer and “warmer” in winter regardless what the operative temperature and standard effective temperature was (Figure 4-34, 4-35, 4-36).

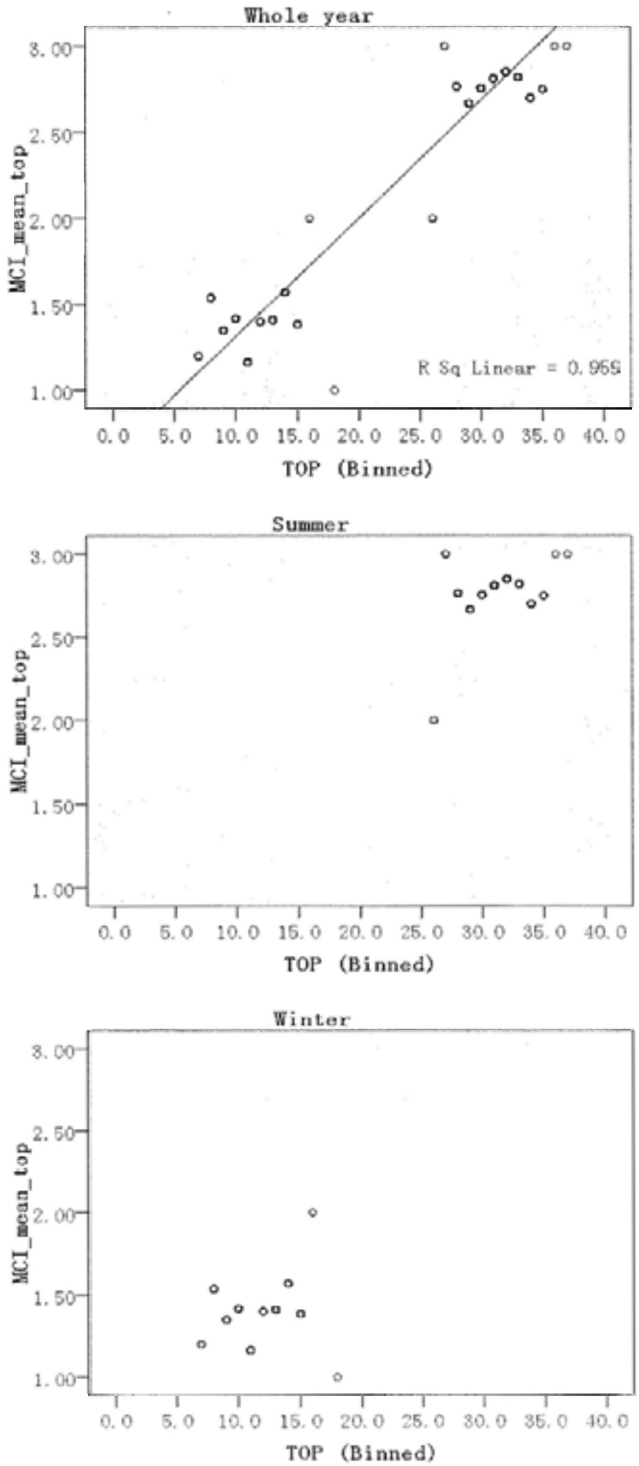


Figure4- 34: Scatted points of mean thermal preference votes against binned operative temperature by season

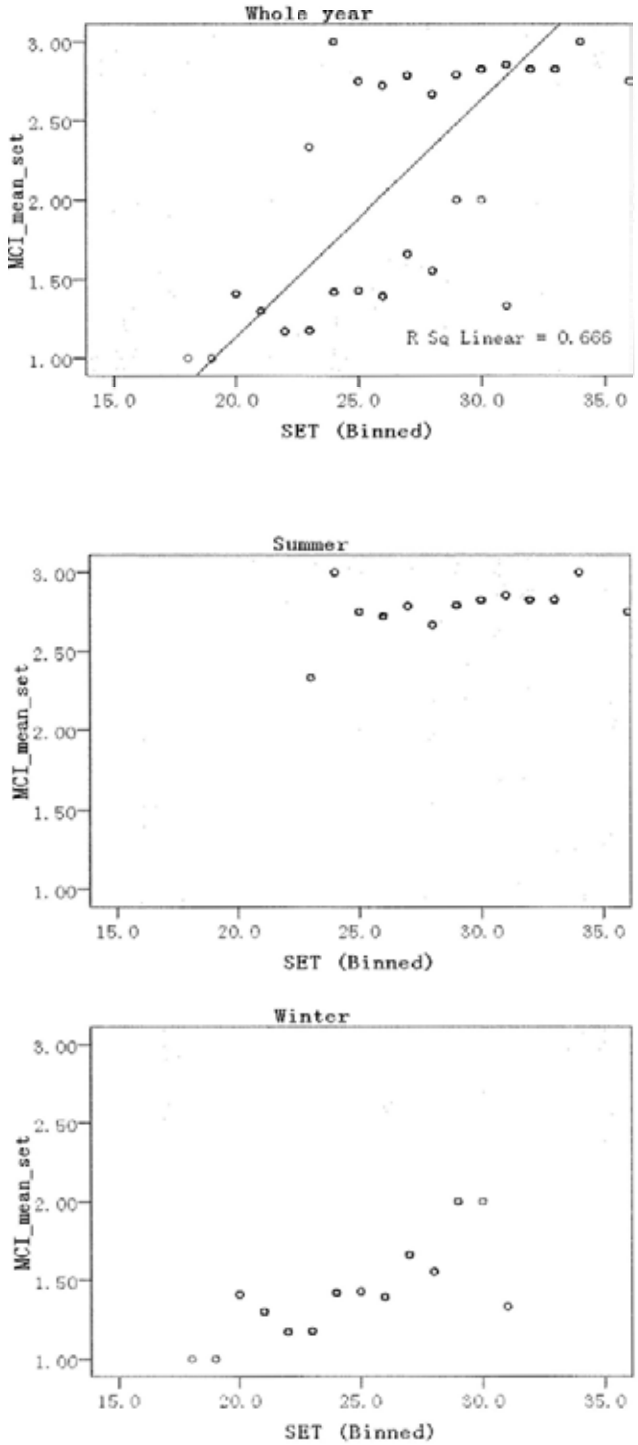


Figure4- 35: Scatted points of mean thermal preference votes against binned standard effective temperature by season

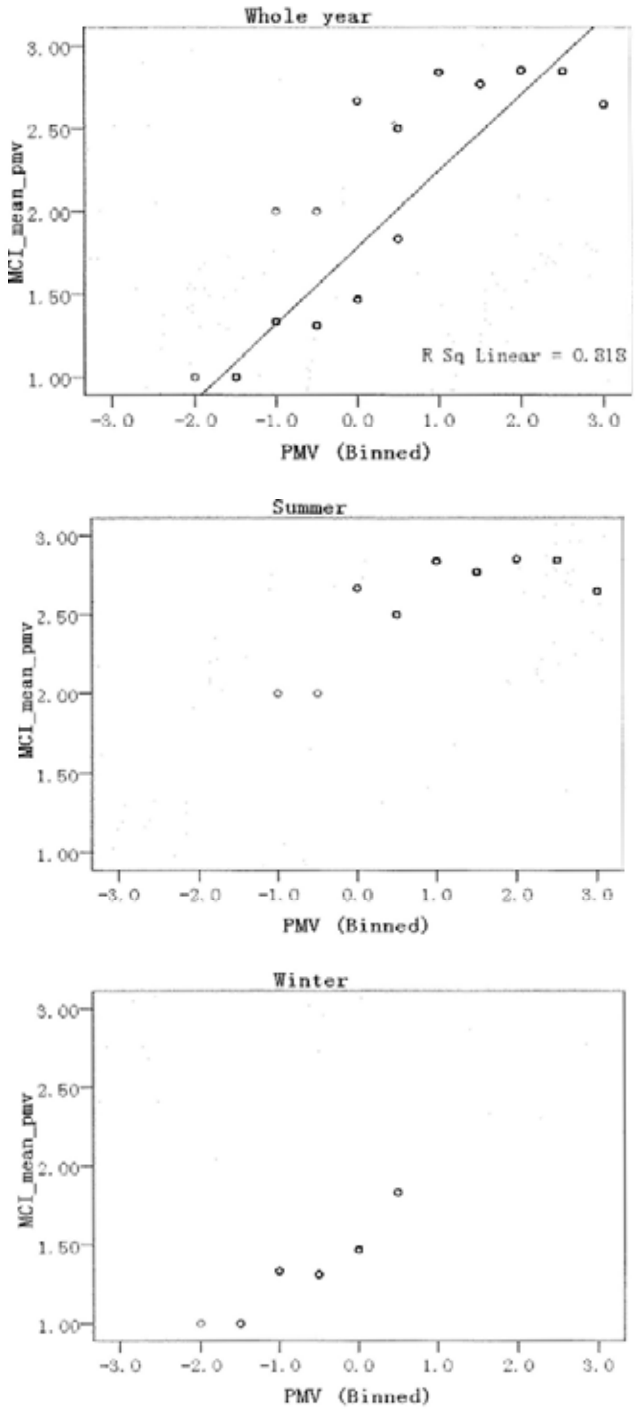


Figure4- 36: Scatted points of mean thermal preference votes against binned predicted mean vote by season

Based on the above results, respondents' changing intention for thermal environments varied greatly between macroscopically different seasons but it was very steady under thermal fluctuation in the same season under HS&CW climatic conditions.

4.3.3.2 Thermal preference votes against thermal indices and thermal sensation

The histograms of thermal preference votes on operative temperature and standard effective temperature also showed little variation within in each season (Figure 4-37, 4-38). Especially the figures of thermal preference distribution against predicted mean votes and thermal sensation votes showed some occupants still preferred cooler conditions in summer and warmer conditions in winter even when they were thermally neutral (PMV=0 or ASH=0) (Figure 4-39, 4-40).

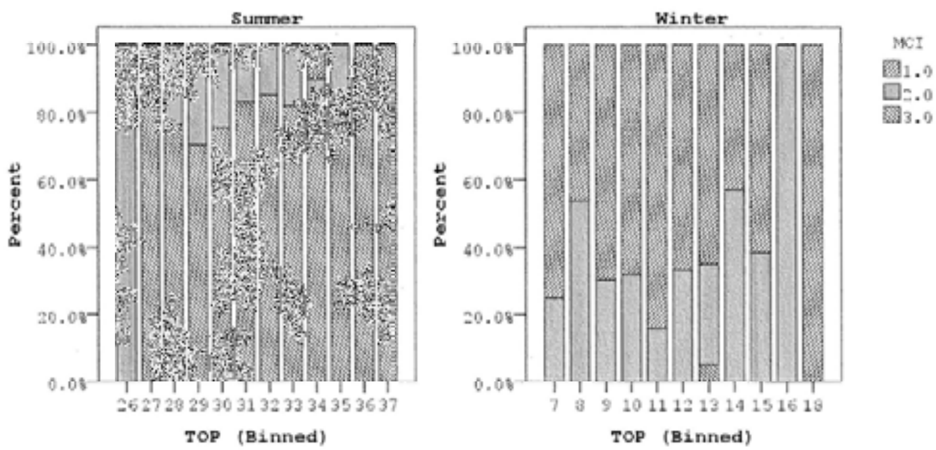


Figure4- 37: Percentage distribution of thermal preference votes along with binned operative temperature by season

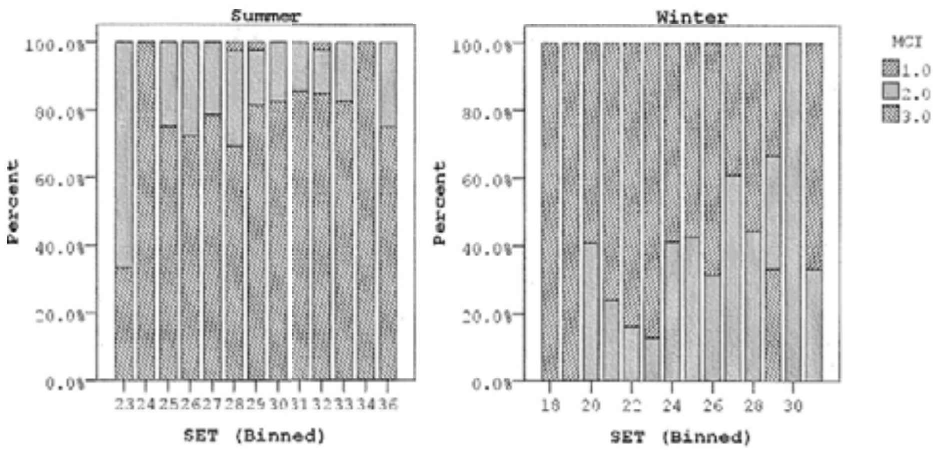


Figure4- 38: Percentage distribution of thermal preference votes along with binned standard effective temperature

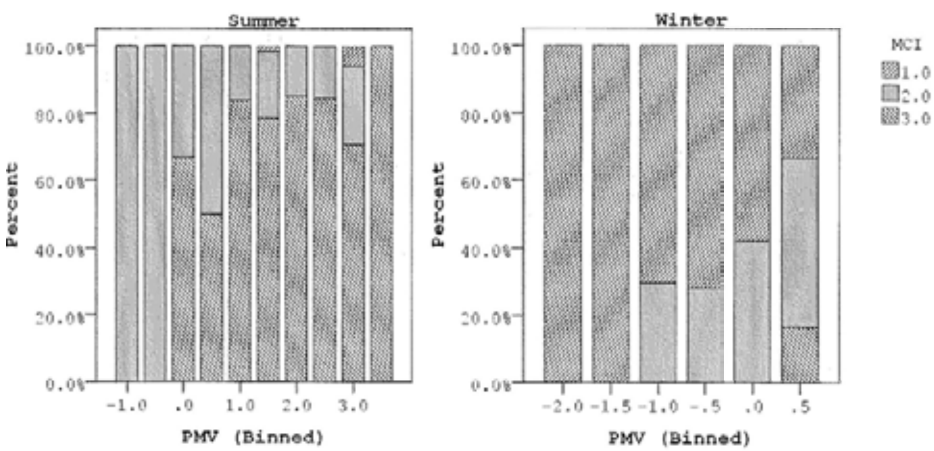


Figure4- 39: Percentage distribution of thermal preference votes along with binned predicted mean votes

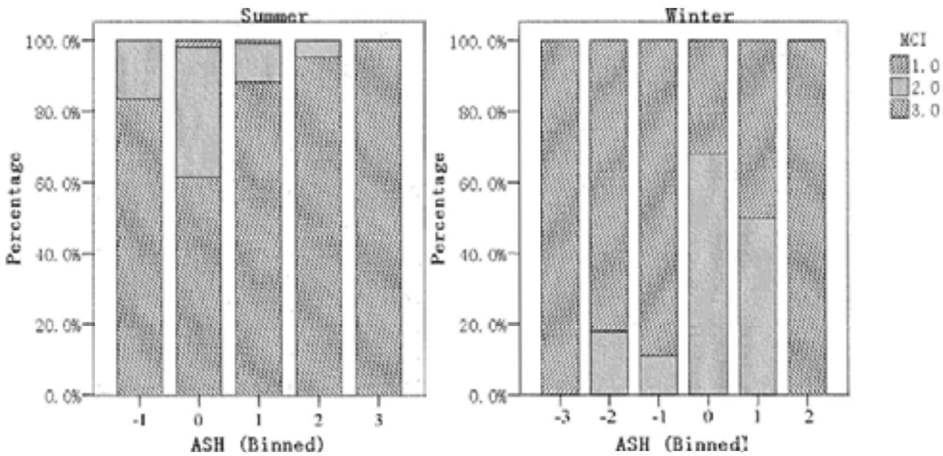


Figure4- 40: Percentage distribution of thermal preference votes along with binned thermal sensation votes

4.3.3.3 Preferred thermal neutrality

Probit Regression analysis was adopted to further investigate respondents' preferred thermal environment because of the little variation between thermal preference votes against thermal indices in the same season (de Dear, Brager et al. 1997). After fitting probit regression curves on the proportion of "warmer" and "cooler" separately against each binned thermal index, the intersection of the two curves was defined as preferred value (of whatever index) for the occupants. All the probit regression models were statistically significant as showed in Figure 4-41, 4-42 and 4-43.

Preferred standard effective temperature was 25.7℃ as shown in Figure 4-42, and preferred Predicted Mean Vote was 0.38 as shown Figure 4-43. But in either season, summer or winter, the data do not permit an optimum to be located.

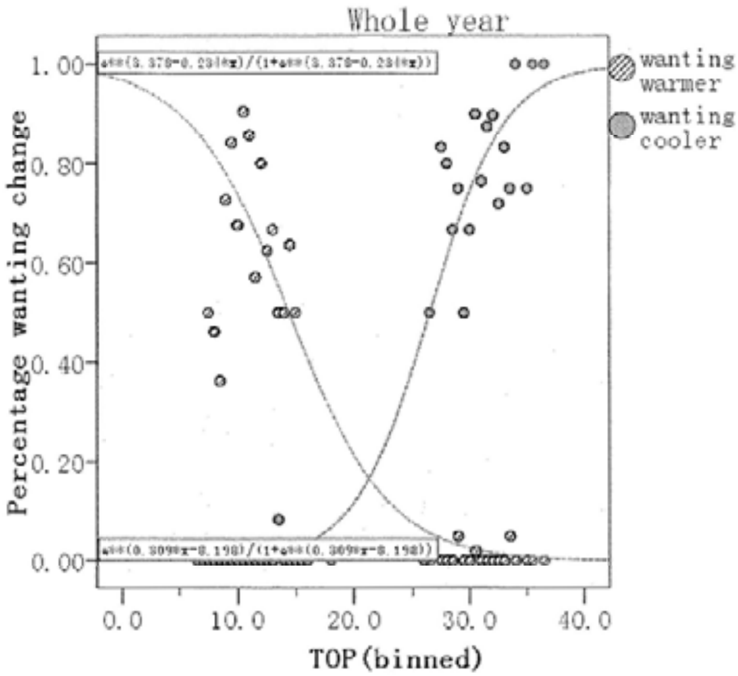


Figure4- 41: Probit regression models fitted to thermal preference percentages against binned operative temperature for the whole year

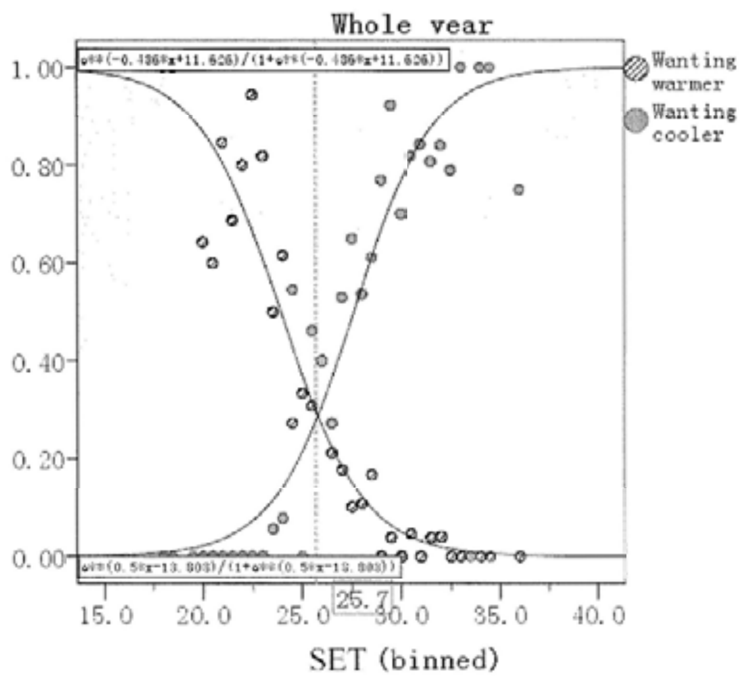


Figure4- 42: Probit regression models fitted to thermal preference percentages against binned standard effective temperature for the whole year

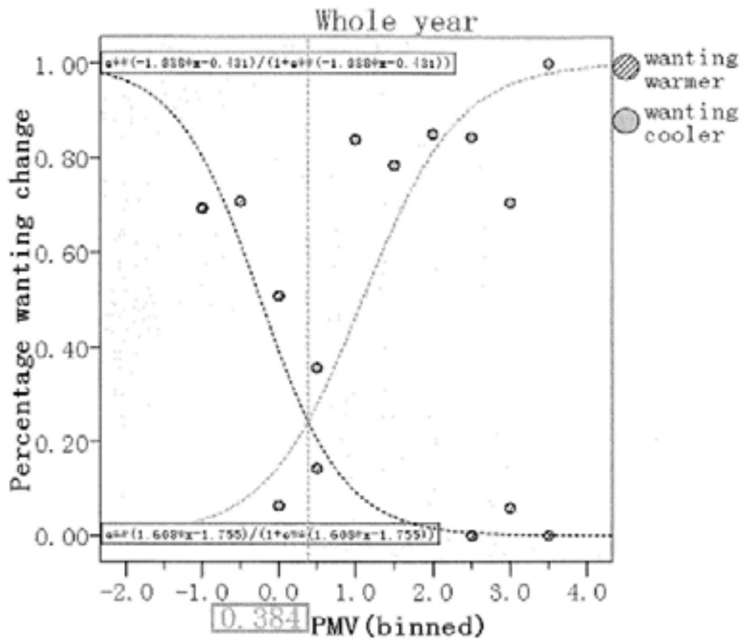


Figure4- 43: Probit regression models fitted to thermal preference percentages against binned predicted mean vote for the whole year

4.3.4 Thermal acceptability (TSA)

Existing thermal comfort standards provide guidelines for 80% thermal satisfaction as mean thermal sensation vote falls within the range of "-0.85~0.85", which is approximately associated with the central three thermal sensation categories of the ASHRAE scale ("slightly cool", "neutral" and "slightly warm"). Is there any difference between this kind of thermal satisfaction and directly assessed thermal acceptability?

In this study, four possible answers were offered to the direct question "Can you accept the current thermal environment, only based on your individual concerns" to investigate respondents' direct acceptability of the corresponding thermal environments ("acceptable", "slightly unacceptable", "unacceptable" and "extremely unacceptable").

Voting of "acceptable" is defined as acceptance of current thermal environment and coded "1", and the other three votes are defined as "unacceptable" and coded "0". Then the mean values of "acceptance" against each value of the binned thermal index both in summer and winter were calculated, and they represents the percentage of overall direct thermal acceptability.

4.3.4.1 Dependence of thermal acceptability on operative temperature

The Figure 4-44 shows the scattered points of acceptability percentage depending on binned indoor operative temperature. It is found that there is no significant linear relationship between occupants' acceptability with operative temperature, but polynomial curve can be estimated to describe the relationship between them well. Over 80% acceptability could be achieved when the operative temperature fall within the range of "14.0℃" to "27.0℃", but maximum acceptability is hard to predict because of data shortage around neutral point.

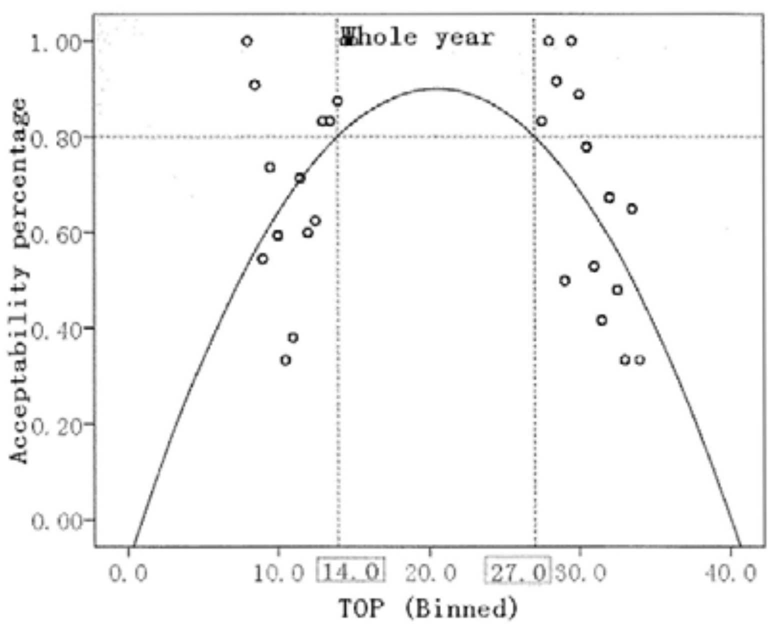


Figure4- 44: Polynomial regression models fitted to acceptability percentages against binned operative temperature for the whole year

Similarly, Figure 4-45 shows that over 80% acceptability could be achieved when the effective temperature fell within the range of "13.0℃" to "28.5℃" and the maximum acceptability percentage of 95.% occurred at the ET of "20.8℃".

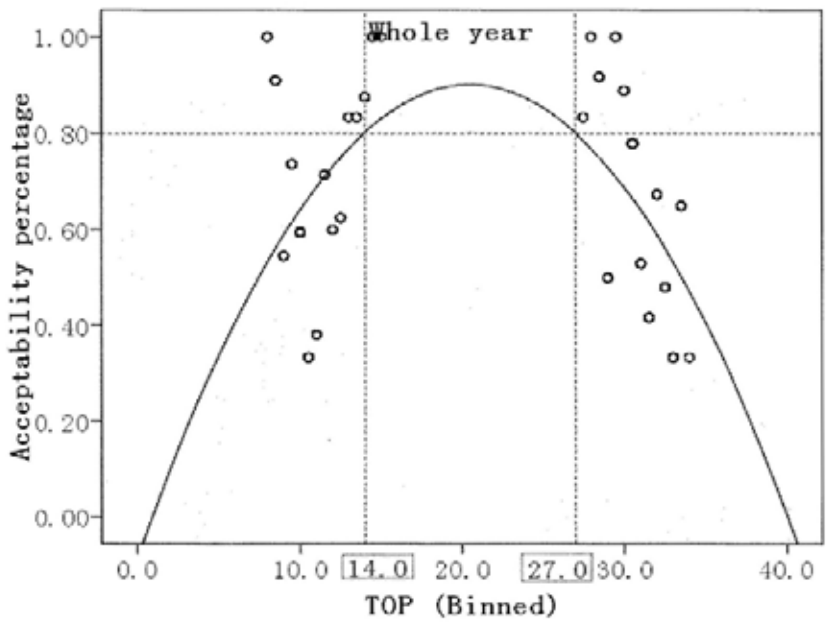


Figure4- 45: Polynomial regression models fitted to acceptability percentages against binned effective temperature for the whole year

4.3.4.2 Dependence of thermal acceptability on standard effective temperature

Figure 4-46 shows the scattered points of acceptability percentage on binned standard effective temperature. But unfortunately, the polynomial regression curve reveals that there was no chance to get 80% acceptability in terms of responding to standard effective temperature, and the highest acceptability value only could get "76%" as the SET value fall in "24.6℃".

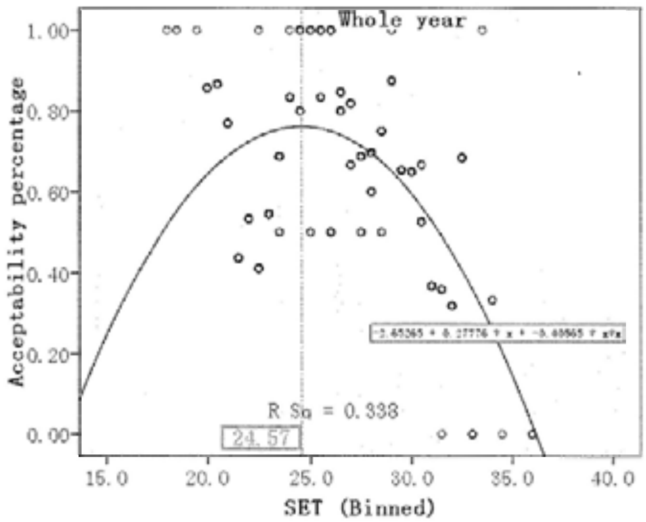


Figure4- 46: Polynomial regression models fitted to acceptability percentages against binned standard effective temperature for the whole year

4.3.4.3 Dependence of thermal acceptability on predicted mean vote

A similar relationship is found in the Figure 4-47 which displays the scattered points of acceptability percentage depending on predicted mean vote. The maximum acceptance (77%) happened when the PMV value equal to "0.45".

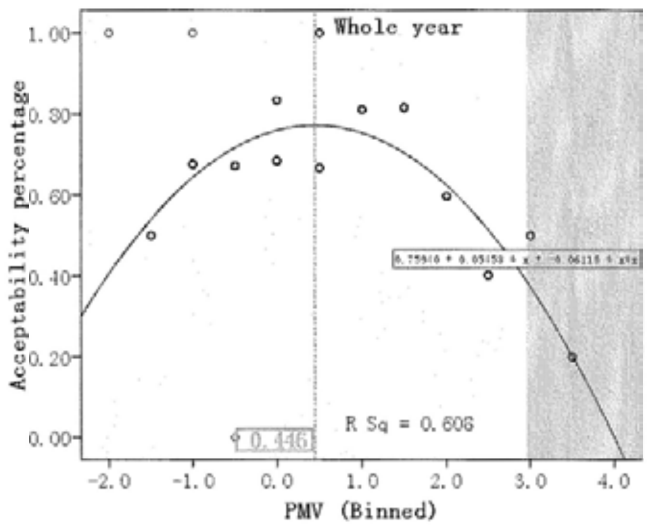


Figure4- 47: Polynomial regression models fitted to acceptability percentages against binned predicted mean vote for the whole year

4.3.5 Humidity sensation (HUS)

In this study, humidity sensation was investigated through five-point scale ("1=too damp", "2=a little damp", "3=just right", "4=a little dry" and "5=too dry"). Under the local high relative humidity conditions, generally occupants tended to vote damp direction in summer with mean value of "2.01", while in winter the mean vote value was "3.00" which meant that they were perfectly satisfied with air humidity. The statistically significant linear regression showed optimal RH in summer was 26% and neutral RH in winter was 58 % (when humidity sensation vote equals to "3") (Table 4-26, Figure 4-48). It indicated that occupants would like complain dampness more in warm environments and therefore their optimal humidity seemed much dry (26%RH).

Meanwhile, if humidity sensation votes falling within the range of "2 to 4" is defined as acceptable for the respondents, based on whole year data, relative humidity range of "10% to 87%" would be acceptable for them.

Table4- 26: Summary of humidity sensation votes responding on relative humidity by season

	Sample size (n)	RH range (%)	Regression equation	Range fulfilling 2<HUS<4	Neutral RH (%)	R^2
Whole year	513	25~90	Y=-0.026*X+4.261	10.0%~87.0%	48.5	0.77
Summer	301	35~80	Y=-0.026*X+4.288	11.1%~88.0%	49.5	0.69
Winter	212	25~90	Y=-0.024*X+4.231	9.6%~93.0%	51.3	0.83

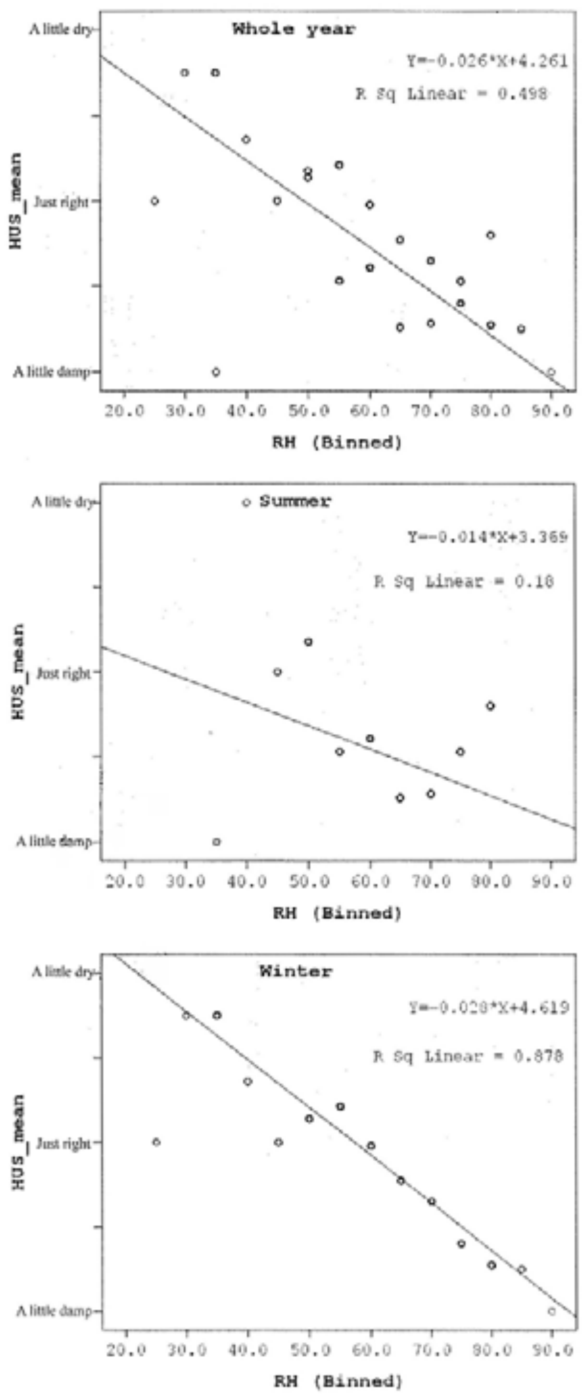


Figure4- 48: Scatted points of mean humidity sensation votes against binned relative humidity by season

Besides relative humidity, vapour pressure was also examined to investigate respondents' humidity sensation variation on absolute humidity. It was found that significant linear regressions also could be drawn between them no matter in winter, summer or the whole year (Table 4-27, Figure 4-49). Although there is humidty sensors in human's body, the respondents most possibly assessed humidity through skin dampness (sweating) in summer and crack lips/xerosis cutis in winter.

Table4- 27: Summary of humidity sensation votes responding on vapour pressure by season

	Sample size (n)	Vapour pressure (Pa)	Regression equation	Neutral Vapour pressure (Pa)	R^2
Whole year	513	250~3750	Y=-0.00023*X+3.145	630	0.574
Summer	301	1500~3750	Y=-0.000605*X+4.291	2134	0.56
Winter	212	250~1250	Y=-0.001151*X+3.856	743	0.955

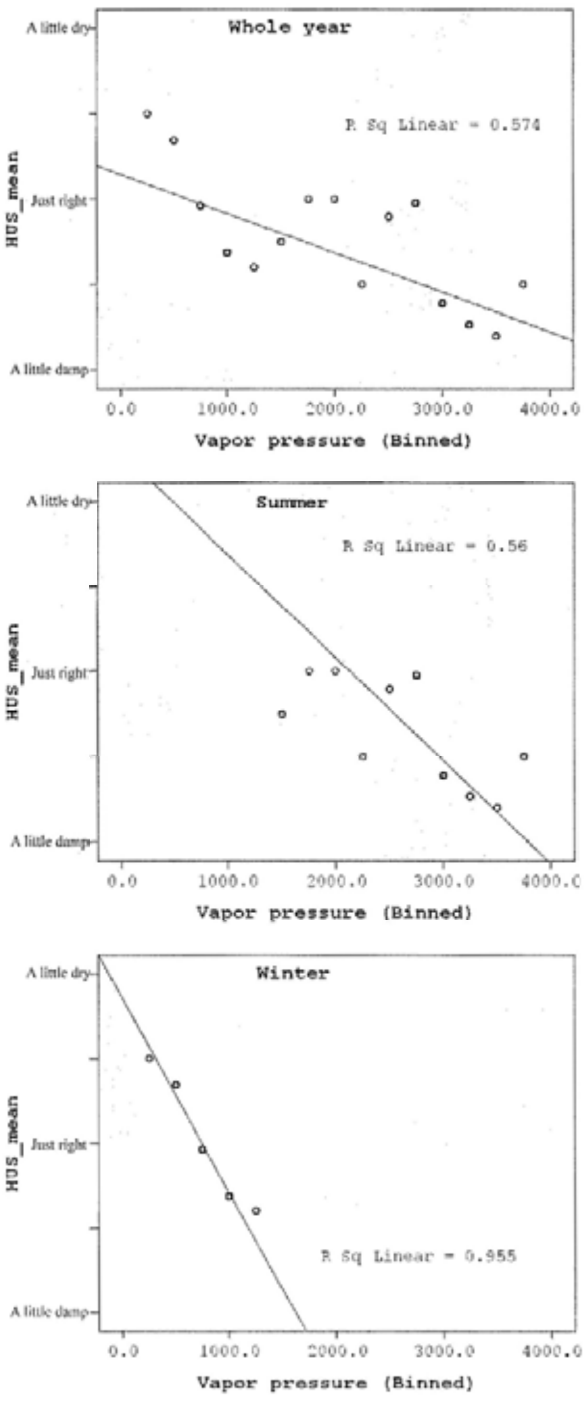


Figure4- 49: Scatted points of mean humidity sensation votes against binned vapour pressure by season

4.3.6 Air movement sensation (AMS)

In this study, indoor air movement was insufficient with the mean value of "0.15m/s" in summer and "0.03m/s" in winter. There was no statistically significant regression models found between air movement sensations against air velocity as is showed in Figure 4-50. In summer, occupants complained that air was too still, even sometimes when the air velocity was higher than 1m/s, or much higher. In winter, most families liked to close the doors and windows, and therefore the indoor air velocity was low at "0m/s" to "0.1m/s" and yet no complaints arose from this still air, perhaps because no cold draughts were wanted.

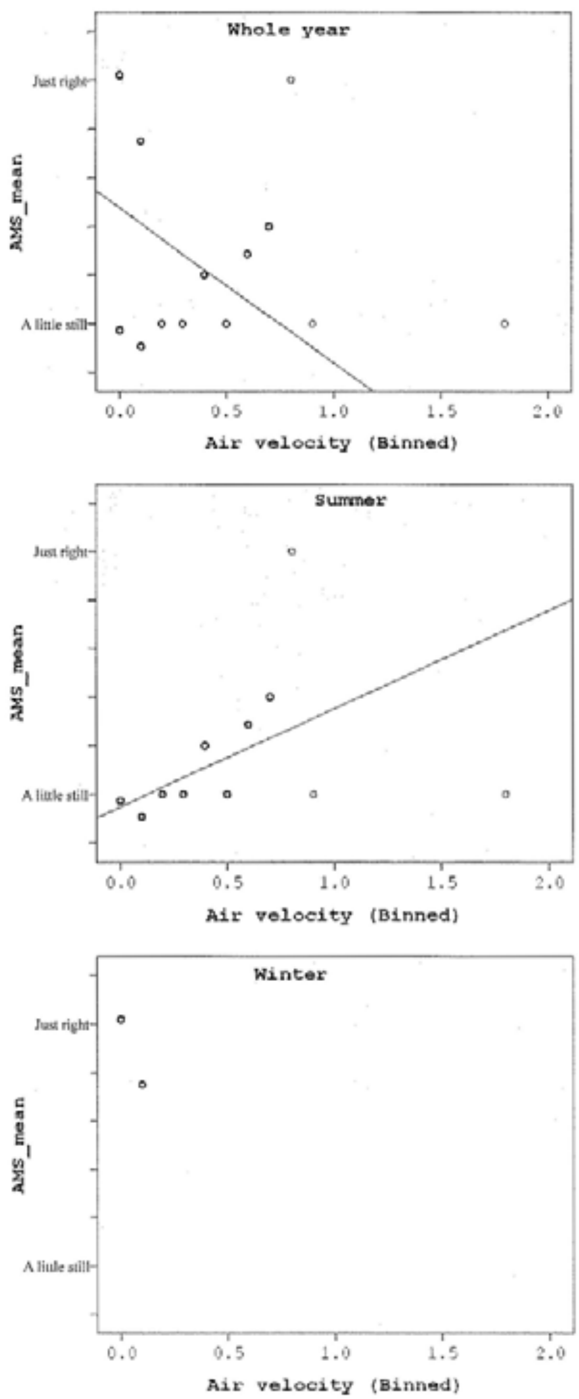


Figure4- 50: Scatted points of mean air movement sensation votes against binned air velocity by season

In summer, with the high temperature and high relative humidity, people preferred more air movement in home presumably to reduce the thermal load on the body more effectively. The maximum indoor acceptable air velocity of 0.8m/s defined by standard seems not suitable for naturally ventilated housing in summer (ASHRAE 2010). The result is consistent with studies conducted in Brazil revealing occupants' much higher air movement requirements in hot humid climates (Candido, de Dear et al.).

4.4 IN-DEPTH CASE STUDIES

Three local urban households (Family A, B, C) and six country households recently from a country area participated in the in-depth study in the 2010 winter. As mentioned in section 3.2.1.6, information on these families' housing characteristics, economic conditions and living habits was collected to explore their possible impacts on occupants' thermal adaptation. 231 sets of thermal perception answers were received to show occupants' real thermal behaviors to their corresponding environments. Appendix H gives detailed information on those households in terms of housing characteristics, economic conditions and living habits.

4.4.1 Housing characteristics, economic conditions and living habits

Housing characteristics:

Family A and B lived in very typical urban housing unit as local residents. During most of the time, their apartments were kept in "free-running" mode and the indoor thermal environments varied little from the outdoor environment despite the building's thermal effect. Family C's apartment was equipped with a free central heating system and they sometimes would complain of over-heated indoor conditions. The families from the countryside lived in more free-running spaces because of fully opened front doors for business, and they suffered a lot from coldness in winter.

Economic conditions:

The heating/cooling expense was not a heavy burden for the investigated urban households in relation to their incomes. They reported that money was not the key direct influencing factor for the utilization of heating/cooling devices at home, while their thermal requirements were highly correlated with their activities. The families from the countryside sacrificed some degree of comfort, probably because of money.

Living habits:

Occupants adapted to the cold environments well through clothing adjustments, control of windows and doors, food and drink intake, intermittent and local heating/cooling patterns and low thermal expectations in all the investigated households. But it seemed that country incomers adapted to cold environments better than the local residents, and Family C had lowest tolerance to thermal discomfort and used heating/cooling device most frequently probably because they had been used to neutral comfort for a long time and could not tolerance worse environments again.

4.4.2 Measured thermal environments and occupants' thermal perception

Table 4-28 summarizes the measured thermal environments and occupants' thermal perception in the in-depth case studies. Family A and B are grouped into naturally ventilated building; Family C presents centrally heated buildings, and country incomers lived in spaces fully opened to the outdoors.

Table4- 28: Summary of measured thermal environments and occupants' thermal perception

	Family A+B (n=82)		Family C (n=42)		New incomers from country (n=107)	
	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev
TA (℃)	11.90	2.33	22.56	1.43	8.36	1.52
RH (%)	69.99	10.46	36.03	6.61	72.76	5.89
O_TA(℃)	10.18	2.68	13.70	2.70	6.70	0.80
O_RH (%)	69.44	9.40	55.94	10.83	75.19	3.22
ASH	-0.86	1.05	0.71	0.83	-0.27	0.56
COMF	0.82	0.53	0.81	0.97	0.26	0.42
MCI	1.28	0.50	2.45	0.50	1.41	0.51
TSA	0.67	0.54	0.67	0.82	0.12	0.35
HUS	2.51	0.53	4.00	0.70	3.04	0.67
AMS	3.09	0.32	2.98	0.15	3.00	0.43
SET(℃)	24.08	2.39	24.55	2.04	22.01	1.86
PMV	-0.47	0.43	-0.234	0.61	-0.75	0.40
CLO	2.26	0.22	1.05	0.20	1.99	0.14
MET	1.23	0.20	1.13	0.16	1.34	0.20

Generally, in winter indoor thermal environments in the naturally ventilated buildings were cold and humid (mean air temperature of "11.9℃" and mean relative humidity of "61"), occupants reported slightly cool (ASH=-0.86), slightly uncomfortable (COMF=0.82) and marginally unacceptable (TSA=0.67), and therefore they would have preferred warmer (MCI=1.28). The centrally heated building provided warmer thermal environments (mean air temperature of "22.6℃" and mean relative humidity of "36"). Occupants reported being slightly warm (ASH=0.71), a little dry (HUS=4.00), slight warmth-discomfort (COMF=0.81) and marginally unacceptable (TSA=0.67), therefore they would have preferred cooler (MCI=2.45). The country incomers lived and worked in very cold and moist environments (mean air temperature of "8.4℃" and mean relative humidity of "73%"), however they reported approximate thermal neutrality (ASH=-0.27), satisfaction (COMF=0.26) and acceptance (TSA=0.21) but would have preferred warmer space (MCI=1.41).

Family A and B were typical urban households with considerable thermal adaption to the local climate; Family C has much higher requirements for indoor thermal comfort with less adaptation; and the six in-comer households definitely had more tolerance to cold thermal environments. Further statistical analysis of impacts from these non-thermal factors will be carried out in Section 5.4.

4.5 SUMMARY

Investigation results presented in this chapter demonstrated local residents' thermal adaptation to hot-humid and cold-damp climate through long time habituation. The descriptive thermal behaviour measurements in both investigations showed respondents had learned to adjust themselves to the local climate through all kind of convenient and simple adjustments including dressing habits, control of windows and doors, food and drink intake, intermittent and local heating/cooling patterns and low thermal expectation. Investigation II not only showed that the hot-humid and cold-damp conditions experienced fell outside the conventional comfort zone, but also reported respondents' general acceptance of those conditions. Additionally, some quantitative analysis between subject thermal perception votes and objective thermal stimulus demonstrated significant correlation within them. The final in-depth case studies revealed that some non-thermal factors, such as housing characteristics, family economic conditions and living habits, probably influenced occupants' thermal tolerance and adaptation level.

CHAPTER 5

DISCUSSIONS

The objectives of this study were to: (1) characterize local residents' thermal behaviour corresponding to the hot-humid and cold-damp climatic conditions in their daily lives; (2) examine local residents' thermal perception using a variety of thermal scales and thermal indices; (3) ascertain acceptable temperature and humidity ranges for occupants in residential buildings in Wuhan addressing adaptation; (4) develop an adaptation model in the local climate context and compare it to the existing thermal models; (5) explore the contextual and non-thermal impacts on adaptive thermal comfort. This discussion not only reflects research results presented above, but also considers the conventional thermal indices' limitations and suggests potential improvements when they are applied in adaptive thermal comfort. It also examines the purpose of thermal environmental design for residential buildings in China urban housing environments.

5.1 WHAT THERMAL ENVIRONMENTS ARE ACCEPTABLE FOR LOCAL RESIDENTS ADDRESSING THERMAL ADAPTATION?

One of main research objectives of this study was to ascertain the acceptable thermal environments for occupants in residential buildings in Wuhan, addressing thermal adaptation. So far, through the analysis of correlations between respondents' real thermal perception and the instantaneous thermal environments they were exposed to, it was possible to attain this aim..

As had been found by Humphreys and Nicol, it was found in this study that a comprehensive thermal index, such as ET^*, SET, PMV, did not improve the explanatory ability with regard to real thermal sensations too much, compared with a single index such as air temperature or operative temperature (see Table 5-1) (Humphreys, Nicol et al. 2007). Meanwhile, temperature is the simplest indicator to guide the daily life and can serve as a practical guide to thermal environmental design and its implementation. Therefore, the discussion of adaptively comfortable thermal environments in this study starts from temperature boundary determination.

Table5- 1: Pearson correlation coefficients between thermal sensation (ASH) and different thermal indices

		ASH	TA_M	TOP	ET*	SET	PMV
ASH	Pearson Correlation	1	.687(**)	.688(**)	.690(**)	.610(**)	.658(**)
TA_M	Pearson Correlation		1	.999(**)	.996(**)	.802(**)	.916(**)
TOP	Pearson Correlation			1	.997(**)	.807(**)	.920(**)
ET*	Pearson Correlation				1	.824(**)	.931(**)
SET	Pearson Correlation					1	.933(**)
PMV	Pearson Correlation						1

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

5.1.1 Temperature range for adaptively acceptable thermal environments

First of all, the definition of "adaptively acceptable" should be clearly stated before any discussion. As discussed in the section 2.1.4, ASHRAE standard 55 has recommended a specific percentage (always 80%) of occupants that constitutes acceptability, and gives values of the thermal environment associated with this percentage (ASHRAE 2010). There are however several methods to define thermal satisfaction, which are: direct acceptability acquisition (TSA); indirect acceptability measurements from thermal sensation votes (ASH), thermal preference votes (MCI) and comfort votes (COMF) (Brager, Fountain et al. 1993). The ideal adaptively acceptable condition should fulfil all the requirements from these four variables.

However, section 4.3.2.2 and section 4.3.3.2 showed that "COMF" and "MCI" varied greatly between different seasons but they were very steady under thermal fluctuation within the same season. Then, "thermal comfort" and "thermal preference" votes are not realistic to distinguish occupants' acceptability according with temperature change. Therefore, if a certain thermal environment could get central category votes of thermal sensation ("-1" to "1") and 80% direct acceptability vote, it will be taken as adaptively acceptable in this study.

Figure 5-1 compares the alternative indirect measurements of acceptability and direct acceptability as a function of operative temperature, and the resulting ranges of acceptable temperature limits that might establish a zone in which the local residents are able to adapt and become thermally comfortable. It is defined as "adaptive comfort zone" in this study.

In this figure, all the polynomial curves represent fits to the data collected from investigation II, and they were weighted by the number of observation at each operative temperature bin. Blue line shows the dissatisfaction percentage against operative temperature which was determined by thermal sensation scale (ASH votes which are outside of the boundary "-1 to 1"); Green line gives the calculated PPD value addressing PMV-PPD tool which was drawn from laboratory experiments; the red line is the direct acceptability assessment to instantaneous thermal environments (percentage of TSA votes of "1, 2, 3"); the purple and gray lines are dissatisfaction percentage based on the thermal comfort scale (comfort and expanded comfort) which had been discussed in Section 4.3.2.2.

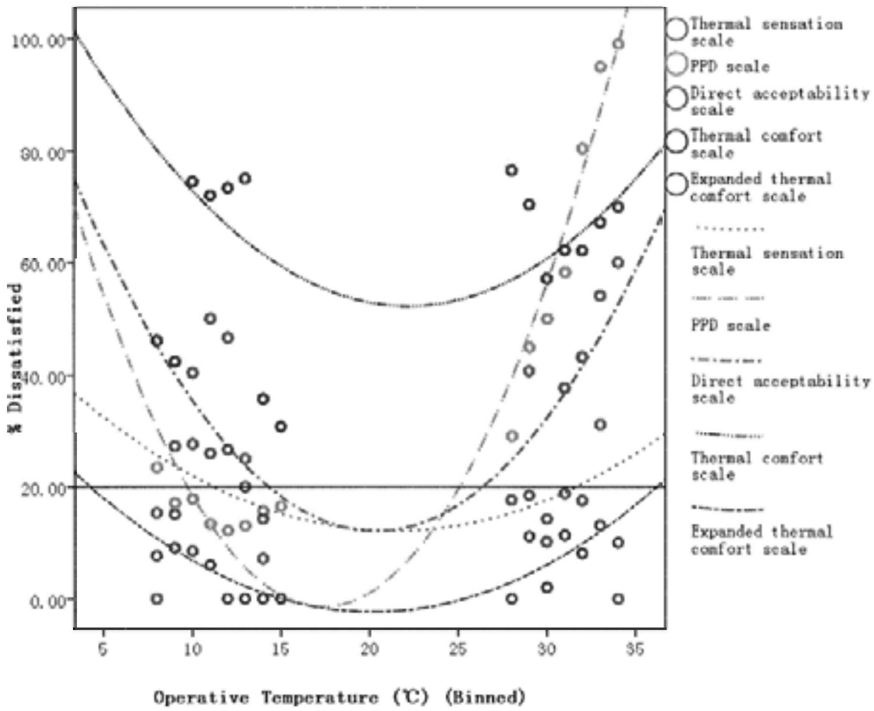


Figure5- 1: Indirect and direct measurements of acceptability

The highest levels of acceptability are achieved by a definition based on the expanded comfort scale, while the lowest levels are based on the thermal comfort scale. Meanwhile, direct acceptability scale give the narrow temperature ranges (14.0℃<TOP<27.0℃) which can satisfy more than 80% occupants compared with indirect measurements of thermal sensation scale (11.1℃<TOP<31.8℃). However, the direct and indirect measurements give quite close minimal level of dissatisfaction (11.9% or 11.8%) when TOP is 20.5℃ or 21.5℃ (Table 5-2).

The graph also illustrates that PPD curve get minimal dissatisfaction level at much lower temperature compared other thermal perception scales. In other words, as a more subjective measurements scale, PPD predicts respondents' optimal acceptance to a cooler position.

Table5- 2: Adaptively acceptable temperature range (20% dissatisfaction) and minimal dissatisfaction points defined by different scale

	TOP range fulfill the criteria (℃)	minimal dissatisfaction TOP point (℃)
Thermal sensation (ASH)	11.1~31.8	21.5
Percentage of predict dissatisfaction (PPD)	9.7~25.1	17.4
Thermal acceptability (TSA)	14.0~27.0	20.5
Thermal comfort (COMF)	N/A	22.3
Expanded thermal comfort	N/A	20.2

Direct thermal acceptability gives strictest criteria for adaptive comfort. Operative temperature range from "14.0℃" to "27.0℃" can fulfil all the requirements from thermal sensation and thermal comfort, therefore it can be drawn as an adaptively comfortable temperature range for local residents and the minimal dissatisfaction level will achieved as temperature fall into the range of "20℃~21℃" from the view of whole year.

5.1.2 Humidity range for adaptively acceptable thermal environments

In this study, acceptable relative humidity range of "10% to 87%" has been found which was illustrated in Section4.3.5. For the humidity and air velocity in naturally conditioned space, there are no limits required by ASHRAE standard 55. Even for the HVAC space, the humidity boundary for thermal comfort suggested by ASHRAE has been often changed in the past one hundred years. The main fluctuation has been the upper humidity limit around 50% to 75% relative humidity or 12 g/Kg humidity ratio. The 90% relative humidity condition is typically the least favourably rated and no lower limit is required (Marc, Edward et al. 1999). Compared with conventional humidity range, the acceptable range of "10% to 87%" drawn from this study is feasible and appropriate for the local residents under HS&CW climatic conditions.

5.1.3 Adaptive comfort model for Wuhan in the HS&CW climatic zone

In the naturally ventilated buildings, an adaptation model can be employed to represent the relationship between indoor neutral temperature and the mean daily outdoor temperature as developed by the research communities (Humphreys and Nicol 1998). The procedure adopted for this study is now explained.

Because of skewed winter or summer data, it is hard to draw adaptation model by using measured thermal sensation and corresponding outdoor temperature directly, and therefore Giffiths Constants method was used to obtain estimates of the neutral temperatures as voting size from each building or each individual was small. A "Griffiths constant (G)" was adopted in order to calculate the estimates of the neutral temperatures, first from each building-visit and then again for each respondent. A linear regression equation was then fitted to each set of neutral temperatures to reveal how the indoor neutral temperature tracked with outdoor temperature (Nicol and Humphreys 2010).

The basic assumptions of using Griffiths constant are "*the neutral temperature can be calculated from the comfort vote by assuming that a comfort vote of zero (neutral) will represent 'comfort'*" and "*a Griffiths constant can describe the relationship between subjective warmth and temperature assuming no adaptation takes place*".

In this study, values of "0.5" and "0.33" for Griffiths constant were tested to calculate the comfortable or neutral temperatures, employing Equation (5-1). The employment of value "0.33" assumes that respondents in this study have the same response to temperature change as people have in the climate chamber (Fanger 1970), and the employment of value "0.5" assumes that those respondents' thermal sensitivity work in the way that is normal in field studies worldwide, such as ASHRAE and SCATs projects illustrated (Humphreys, Rijal et al. 2010).

$$C = G\ (Top - Tcomf) \qquad (5\text{-}1)$$

C: Mean thermal sensation vote in each building (neutral is coded zero)

G: Griffiths constant (scale units per unit temperature change)

Top: Mean operative temperature in the same building

Tcomf: Calculated neutral temperature in the same building

Figure 5-2 displays the scattered neutral temperatures against the outdoor temperatures in each individual building. In this figure, Green triangle points represent the calculated neutral temperature for a Griffiths constant of "0.5" and blue circle points were calculated for a Griffiths constant of "0.33". In graph, outdoor temperature was defined as "0.2" timing average air temperature of previous day plus "0.8" timing running mean temperature of previous day (Nicol and Humphreys 2007). It was found that neutral temperature was about "10℃" to "15℃" in winter while "25℃" to "35℃" in summer, and the regression coefficient was around "0.6" no matter whether a Griffiths constant of "0.5" or "0.33" was employed.

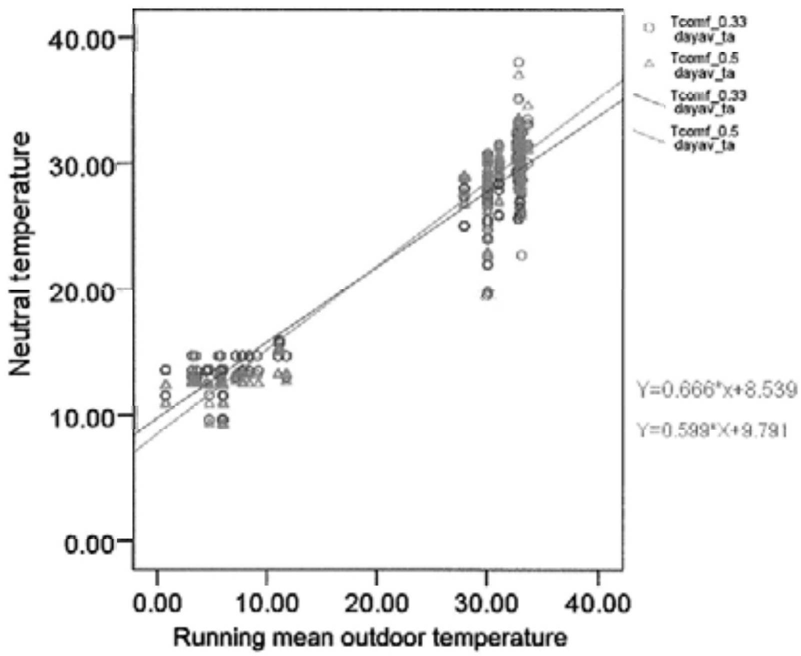


Figure5- 2: Neutral temperature against outdoor temperature each point represents an individual building-visit

Similarly, Figure 5-3 displays the scattered neutral temperatures, drawn from each individual respondent, changing with outdoor temperatures. Green triangle points represent the calculated neutral temperature addressing Griffiths constant of "0.5" and blue circle points were calculated addressing Griffiths constant of "0.33". It happened again that no matter which Griffiths constant was employed, and no matter whether they were calculated from each building or each respondent, the final adaptive models are vey close to each other. The final model could be approximately simplified as "Tc=0.6* Tout+9.8".

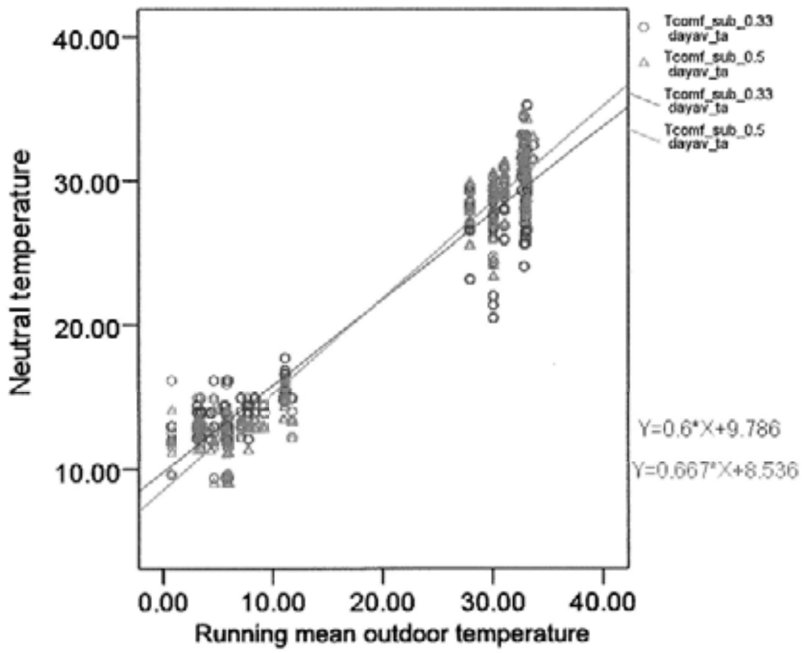


Figure5- 3: Neutral temperature against outdoor temperature each point represents an individual respondent

Based on standard whether data in Wuhan, the mean outdoor temperature range is from "0℃" to "33℃" (Jiang, 2005), and therefore the neutral temperature could be calculated from 9.8℃ to 29.6℃ based on this adaptation model.

Comparing this result with the adaptively acceptable temperature range drawn in section 5.1.1 and the acceptable humidity range drawn in section 5.1.2, the adaptation thermal model for local residents in the local climatic conditions is suggested as the following equation:

$$Tc=0.6*Tout+9.8 \quad (14.0℃<=Tc<=27.0℃,\ 10\%<=RH<=87\%) \qquad (5\text{-}2)$$

Tc: comfortable indoor operative temperature,

Tout: Mean outdoor temperature

RH: relative humidity

5.2 Comparisons with Previous Adaptive Thermal Comfort Studies

One of main research interests of adaptive thermal comfort is to further seek its operation mechanism and generalize some patterns through meta-analysis of thermal comfort field studies, which will contribute to the comprehensive understanding of adaptive thermal comfort. The diversity of adaptive thermal comfort studies around the world has been discussed in Chapter 2 section 2.2.2, and comparisons with other researchers' work is very helpful not only to give some insight into general adaptive thermal comfort research, but also to give insight into localized adaptive thermal comfort under the specific climate and housing conditions.

5.2.1 Comparisons with international adaptive thermal comfort studies

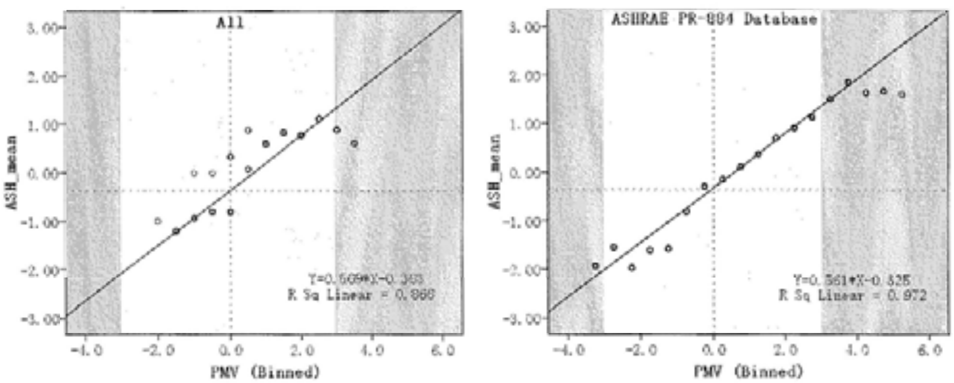
5.2.1.1 Comparison of thermal sensitivity and thermal neutral

ASHRAE research project-884 database has been the biggest open database of adaptive thermal comfort research worldwide until now and it covers 109 air conditioned buildings and 44 naturally ventilated building. For the comparison with this study, only data coming from naturally ventilated buildings are involved. The raw data are downloaded freely from internet webpage[41].

First of all, the discrepancy between "thermal sensation votes (ASH)" with "predicted mean votes (PMV)" is very similar between ASHRAE RP-884 database and this study. The fitted linear regressions of "ASH" against on "PMV" have very similar coefficient values

[41] http://sydney.edu.au/architecture/staff/homepage/richard_de_dear/ashrae_rp-884.shtml

("0.569" from this study and "0.561" from ASHRAE PR-884 database) ($p<0.001$) and similar constant values ("-0.363" from this study and "-0.325" from ASHRAE RP-884 database) (Figure 5-4). These two studies both indicate that PMV overestimates occupants' thermal sensitivity approximately twofold in the naturally ventilated buildings, and when PMV predicts neutrality, the occupants feel on average slightly cooler than neutral.



a: this study b: ASHRAE RP-884 database

Figure5- 4: Comparison of thermal sensation against predicted mean vote

Except of the direct comparison of ASH and PMV, the overestimation of PMV on thermal sensitivity in field also could be fingured out through the comparision of their dependence on TOP. Figure 5-5 displays the scattered points of ASH/PMV against binned TOP and the linear regression models derived from them. The gradient values ("0.126" of PMV, "0.083" of ASH) also displayed that the changing rate of ASH on TOP was only around 66% of PMV changing rate on TOP.

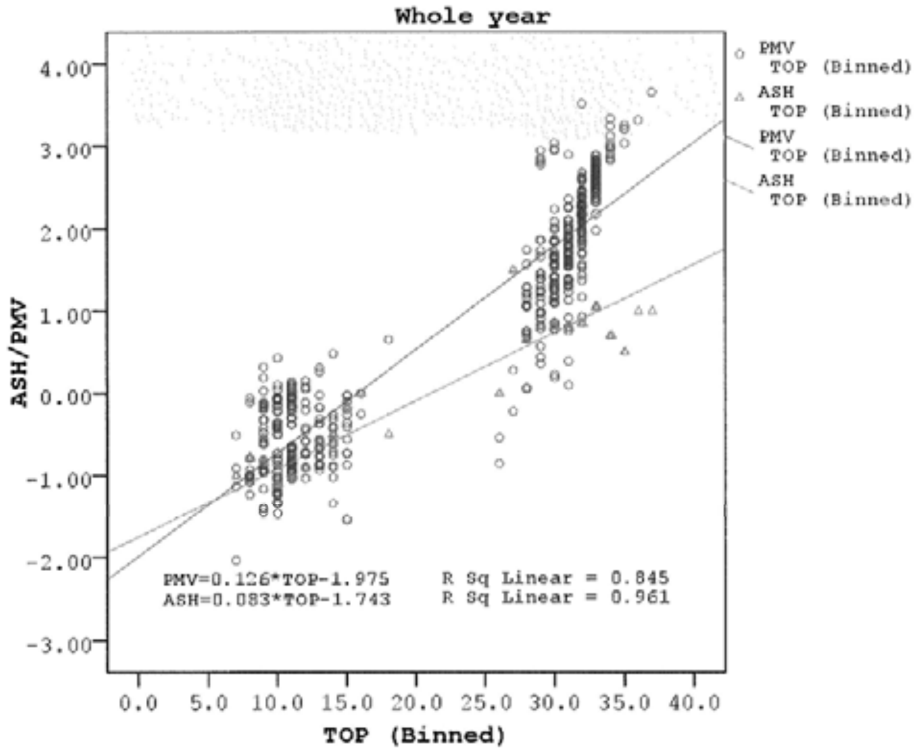


Figure5- 5: Comparison of ASH/PMV against binned operative temperature

The dependence of thermal sensation on standard effective temperature also repeats that "SET" overestimates occupants' thermal sensitivity in the naturally ventilated buildings as showed in Figure 5-6. The results of the two regression equations are reasonably consistent with each other in terms of regression coefficient and neutral point (coefficient of "0.192" and corresponding neutral point of "26.26℃" in this study, and coefficient of "0.154" and corresponding neutral point of "25℃" in the ASHRAE RP-884 database) ($p<0.001$). Comparing the overall relationship between standard effective temperature with humans' thermal sensation for sedentary clothed subjects which was quoted by Gagge from Hardy, the empirical results from field studies are consistent in terms of thermal neutral points but inconsistent in terms of thermal sensitivity (coefficient of "0.284" and neutral point of "25℃" in Gagge's quotation) (Gagge, Stolwijk et al. 1971). It indicates that although Standard

Effective Temperature overestimates occupants' thermal sensitivity in hot and cold environments, it predicts occupants' thermally neutral temperature reasonably well, for the occupants in these naturally ventilated buildings.

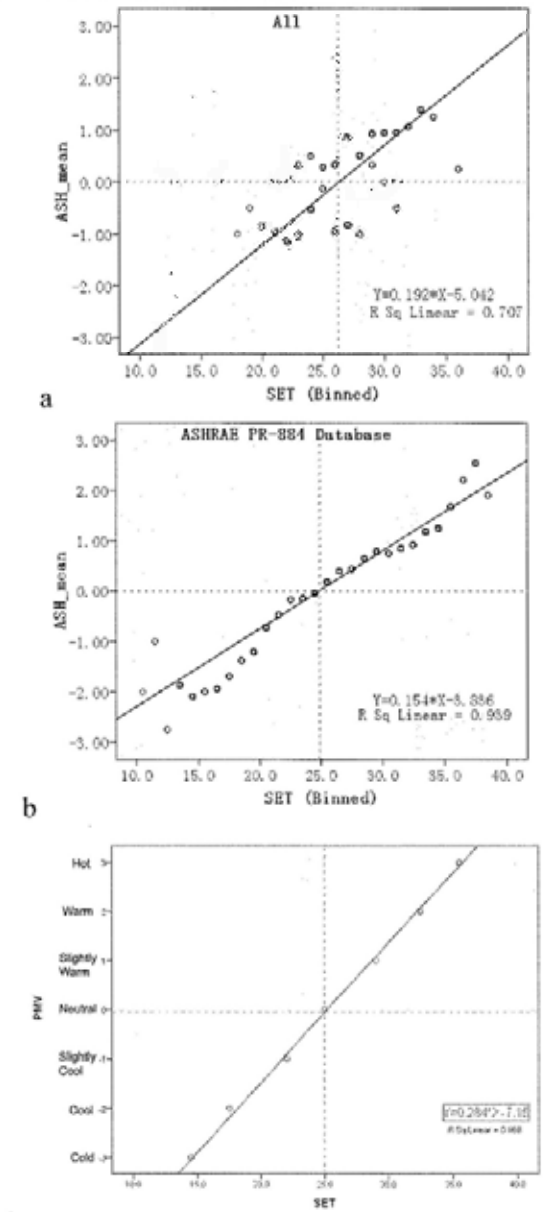


Figure 5-6-a: Scattered points from this study

Figure 5-6-b: Scattered points from ASHRAE RP-884 database

Figure 5-6-c: Scattered points translated from Gagge's SET and quotation from Ref Hardy, 1970

Figure5- 6: Comparison of mean thermal sensation against binned standard effective temperature

Generally, the results drawn from this study are consistent with international database in terms of thermal sensitivity and thermal neutral of adaptive thermal comfort in the naturally ventilated buildings from the whole year view. PMV tool approximately overestimates thermal sensitivity by a factor of "2" and SET predicts thermal neutral very well. Accordingly, conventional indices of PMV has the capacity to appropriately evaluate thermal environments and predict occupants' adaptive thermal comfort if some correction coefficient could be adopted. For this study, based on the discrepancy of real thermal sensation (ASH) and predicted mean vote (PMV), conventional PMV index can be improved by adding expectation value of "0.6" and therefore the new PMV could be written Equation 5-3. Meanwhile, occupants can get thermal neutral as SET arrives to "25℃~26℃" in naturally ventilated buildings.

$$PMVnew=0.6*PMV-0.36 \qquad (5\text{-}3)$$

5.2.1.2 Comparison of adaptation models

Compared with other adaptation models derived from different databases in the international research communities as showed in Table 5-3, the adaptation model drawn from this study shows the higher adaptation ability of the local residents in HS&CW climatic conditions in China. The regression coefficient value indicates the changing rate of occupants' adaptively comfortable temperature against outdoor temperature. The value of "0.6" drawn from this study is almost twice the value of "0.31" drawn from ASHRAE RP-884 database (de Dear, Brager et al. 1997) as well as value of "0.33" drawn from EU project Smart Controls and Thermal Comfort database (Nicol and Humphreys 2009).

The local residents' high adaption ability probably is shaped by the local climatic characteristics; the hot-humid summer and cold-damp winter, and also by non-thermal factors including housing characteristics, living experiences and thermal expectation, economic conditions and consumer-values, and living habits, etc. Some non-thermal impacts on adaptive thermal comfort will be further discussed in section 5.4.

Table5- 3: Results comparisons of adaptation model between this study and other international research

Database	Researcher	Year	Adaptive model
EU project Smart Controls and Thermal Comfort contributing European standard EN15251	Nicol and Humphreys	2009	Tc =0.33* Tout + 18.8
ASHARE RP-884 contributing ASHRAE Standard 55	de Dear, Brager et al	2005	Tc =0.31* Tout + 17.6
This study	Author	2010	Tc =0.6* Tout + 9.8

5.2.2 Comparison with previous adaptive thermal comfort studies conducted in China

Some studies about adaptive thermal comfort in China were mentioned in Chapter 2 section 2.4. During the following discussion, only comparisons of acceptable thermal environments in naturally ventilated buildings and adaptation models are addressed.

5.2.2.1 Comparison of acceptable thermal environments

The Table 5-4 summarizes the main results from previous adaptive thermal comfort studies in naturally ventilated buildings in China (Xia, Zhao et al. 1999; Tang 2001; Ye 2005; Han, Zhang et al. 2007; Li, Liu et al. 2007; Li, Yang et al. 2008; Han, Yang et al. 2009; Li, Yu et al. January 10, 2011). It shows that acceptable thermal environments vary from each other for different locations and studying seasons. Generally, the subjects' metabolic rate is very similar, and centres on the range "1.2met" to "1.3met". Clothing value varies from season and location. Residents in this study change their clothes with the climate variation to the greatest extend with minimum of "0.03clo" in summer and maximum of "2.4clo" in winter.

Table5- 4: Comparisons of comfortable thermal environments derived from field studies in China

Researcher	Publication Year	Location	Season	Building type	Clothing value /metabolic rate	Suggested acceptable thermal environments
Xia, Zhao et al.	1999	Beijing	Summer	Naturally ventilated residential buildings	0.31clo; 1.2met	maximum ET=30℃ for 80% acceptability
Tang	2001	Chongqing	Summer	Naturally ventilated Residential buildings	0.5clo; 1.2met	PMV<=1
Ye, X.	2005	Shanghai	Whole year	Naturally ventilated buildings	Iclo=1.419-0.036TA	TOP=14.7~29.8℃ for 80% acceptability
Li, B., J. Liu, et al.	2007	Chongqing	Winter	Naturally ventilated classrooms	1.42clo; 1.2met	TA= 14.04~24.2℃ for 80% acceptability
Han, J., G. Zhang, et al	2007	Changsha, Guangzhou, Shenzhen	Summer	Naturally ventilated Residential buildings	0.54clo; 1.3met	Neutral ET=28.6℃ TOP=22.0~27℃ for 75% acceptability
Li, J., L. Yang, et al	2008	Nanyang	Summer & Winter	Naturally ventilated Residential buildings	0.4clo in summer; 1.4clo in winter; 1.2met	TA=12.5~28.4℃ for 80% acceptability
Han, J., W. Yang, et al.	2009	Changsha &Yuping	Winter	Naturally ventilated Residential buildings	2.0clo; 1.2met	Minimum Neutral TOP=14℃
Li, Yu et al.	2011	Chongqing, Shanghai, Chengdu, Wuhan, Changsha, Hefei, Nanjing, &Hangzhou	Summer& Winter	Residential Buildings	0.22-0.76clo in summer; 0.61-1.83cloin winter; 1.0-1.2met	Indoor temperature=16.3~28.1℃ for 80% acceptability
This study	2007 ~ 2010	Wuhan	Summer & Winter	Naturally ventilated Residential buildings	0.03clo in summer; 2.4clo in winter; 1.3met	TOP=14.0~27.0℃ for 80% acceptability ET=13.0~28.5℃ for 80% acceptability

The suggested acceptable thermal environments are presented in the form of air temperature range, operative temperature range or effective temperature range. (For an indoor thermal comfort study, the discrepancy between air temperature and operative temperature is usually quite small, and so for the following discussion, no distinction is made beween them). The temperature ranges are very similar, especially under similar climatic conditions. Lowest acceptable indoor temperature in winter fulfilling 80% satisfaction is around 12.5℃~14.7℃, and highest acceptable indoor temperature in summer centres on 27.0℃~29.8℃.

Through this comparison, another phenomenon could be found. It is that the acceptable thermal environments calculated using the regression methods vary with the season. It is probably because that the regression results are highly associated with independent variable's magnitude, and temperature distributions (whether, TOP or SET) in respective seasons are totally different. For the HS&CW zone, the climatic variation through one year determines that consideration of both summer and winter is necessary for the study of adaptive thermal comfort.

Based on these comparisons, it is very hard to find a specific benchmark temperature for naturally ventilated buildings, but an adaptively acceptable thermal range still can be approximately established for local residents, such as the acceptable operative temperature range of "14.0℃~27℃" drawn from this study, and is useful to guide more sustainable indoor thermal environment design,

5.2.2.2 Comparison of adaptation models

Table 5-5 and Figure 5-7 summarize adaptation models drawn from different studies focusing on HS&CW climate in China (Ye 2005; Han 2008; Li, Liu et al. 2008; Li, Yu et al. 2011). Whether a Griffiths Constant of "0.33" or "0.5" was employed in this study, the adaptation model shows its consistence with Han Jie's and Li Junge's results drawn from same kind of buildings. The model drawn from the present study predicts a comfortable temperature in summer (outdoor temperature falling in "25℃~35℃") very similar to that of Ye's model, but suggests a much lower comfortable temperature in winter (outdoor temperature falling in "0℃~15℃) than Ye's. Li, B., et al' model is nearer to the model drawn from worldwide database, with less adaptation as mentioned above.

Table5- 5: Comparisons of adaptation model drawn in the HS&CW climatic zone in the residential buildings

Researcher	Year	Location	Season	Building type	Adaptive model	Acceptable Temperature Range (℃)	R
This study G=0.33	2007 ~2010	Wuhan	Summer & winter	Naturally ventilated Residential buildings	Tc =0.6* Tout + 9.786	14.0~27.0	0.96
This study G=0.5	2007 ~2010	Wuhan	Summer & winter	Naturally ventilated Residential buildings	Tc =0.667* Tout + 8.536	14.0~27.0	0.98
Han, Jie	2008	Changsha	Summer & winter	Naturally ventilated Residential buildings	Tc =0.67* Tout + 10.32	14.0~32.75	0.83
Li, Junge	2008	Nanyang	Summer & winter	Naturally ventilated Residential building	Tc =0.607* Tout + 10.092	13.6~27.3	0.83
Ye, Xiaojing	2005	Shanghai	Summer & winter	Naturally ventilated Residential buildings	Tc =0.422* Tout + 15.122	14.7~29.8	0.74
Li, B., et al.,	2011	Chongqing, Shanghai, Chengdu, Wuhan, Changsha, Hefei, Nanjing, &Hangzhou	Summer & winter	Residential buildings	Tc =0.294* Tout + 14.989	13.6~28.1	0.74

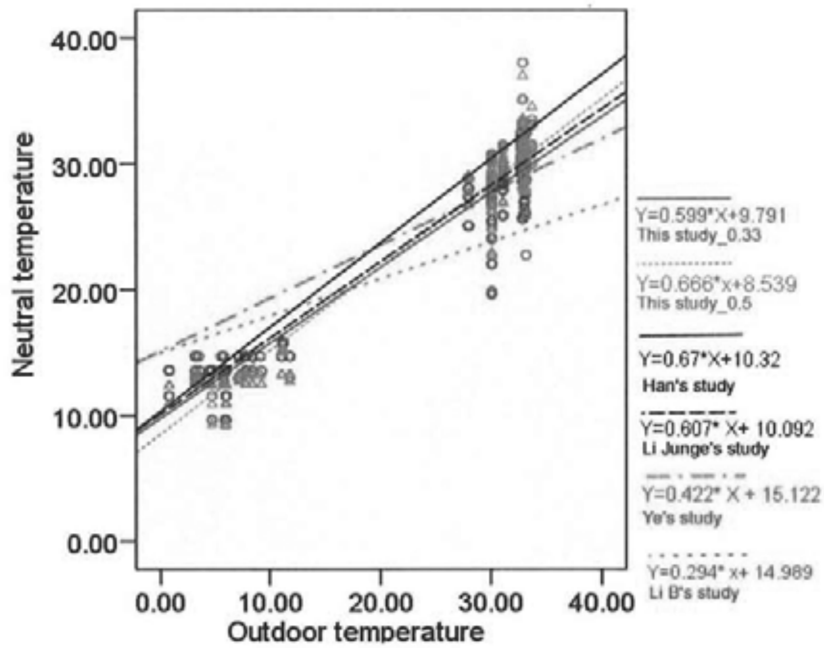


Figure5- 7: Comparisons of adaptive models derived from field studies in China

The variation of these adaptation models probably comes from investigation location, associated climatic and respondents. Both Han Jie's and Li Junge's studies were conducted in residential building in Hunan province where the climatic condition is mostly like Wuhan's, and their models results are similar to those drawn from the present study. Li Baizhan's model was drawn from eight cities and its adaptive model was highly influenced by winter data. Ye's model was drawn from university students living in university dormitories in Shanghai, probably the bias from young respondents in dormitories could not be ignored to some extent.

5.3 Limitations and Potential Improvements of Conventional Thermal Indices Applied in Adaptive Thermal Comfort

5.3.1 Thermal satisfaction and thermal sensation vote

Based on Fanger's equation, thermal dissatisfaction (PPD) can be drawn from PMV value employing Equation 5-4. Can it give good prediction for occupants' satisfaction in naturally ventilated buildings? This section tries to analyse the relationship between occupants' thermal comfort vote and thermal sensation vote which is named as "ASH-DP"[42] and compares it with PMV-PPD tool.

$$PPD = 100 - 95 * \exp(-0.3353 * PMV^4 - 0.2179 * PMV^2) \qquad \textit{(5-4)}$$

As mentioned in Chapter 4.3.2, there are two methods to draw occupants' percentage of dissatisfaction through direct thermal comfort votes, which are named as comfort dissatisfaction and expanded comfort dissatisfaction. Figure 5-8 displays two groups of dissatisfaction percentages against thermal sensation vote (ASH). Solid-dot points represent the comfort dissatisfaction percentage and open-dot points represent expanded comfort dissatisfaction percentage. The red line draws the standard curve of PMV-PPD Equation 5-4.

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[42] ASH: thermal sensation vote; DP: dissatisfaction percentage.

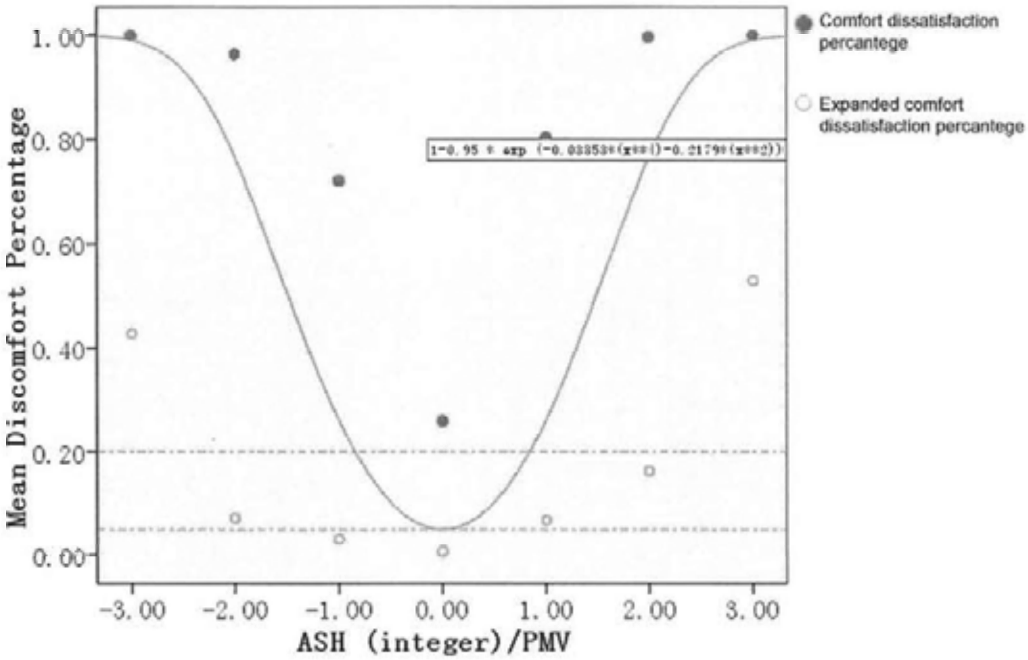

Figure5- 8: Scatterred plots of dissatisfaction percentage against to binned thermal sensation votes

It can be found that both when people are feeling warmer than neutral and cooler than neutral, the standard curve of PMV-PPD did not well agree with direct thermal comfort voted by respondents. PMV-PPD overestimated the comfort dissatisfaction percentage while it underestimated the expanded dissatisfaction percentage. The generally symmetric pattern of the scattered points indicates a symmetrical relationship of dissatisfaction percentage on thermal sensation vote in warmness and coldness. As discussed in section 5.2.1.1 on thermal sensitivity, if real thermal sensation vote (ASH) could be obtained from PMV calculation through employing correction coefficient, for instance as Fanger's expectation value, it is also hopeful to further predict occupants' thermal comfort dissatisfaction with the aid of correction coefficient because of the similarity between PMV-PPD obtained in thermal chamber and ASH-DP obtained from field study. For the correction part, how to define "satisfaction" and "dissatisfaction" become critical. At least, four-point scale of "comfortable, slightly uncomfortable, uncomfortable and extremely uncomfortable" [43] is hard to give good interpretation for occupants' perception on thermal comfort based on this study results, and probably more sophisticated scaling is required in future work.

5.3.2 Seasonal variation

In Wuhan, the hot-humid summer and cold-damp winter is the most remarkable climatic feature, and presents a double challenge for building thermal environments. Is there any seasonal difference in the behaviour of the conventional thermal indices applied to adaptive thermal comfort? This section will address the problem from the view of the discrepancy between "ASH" and "PMV" in the different seasons.

What is the seasonal difference?

Firstly, by comparing Table 4-15 with Table 4-16, for local residents in the naturally ventilated buildings, "PMV" overestimated occupants' warm sensation in summer by "1.1" units, but only underestimated occupants' cool sensation by "0.3" units in winter. The much bigger discrepancy between "PMV" and "ASH" in summer indicates that PMV predicts the mean vote better in winter. In other words, residents can achieve more extensive adaptation in summer than in winter, based on the benchmark of PMV.

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[43] Corresponding scale in Chinese is "舒服, 有点不舒服, 不舒服, 极其不舒服".

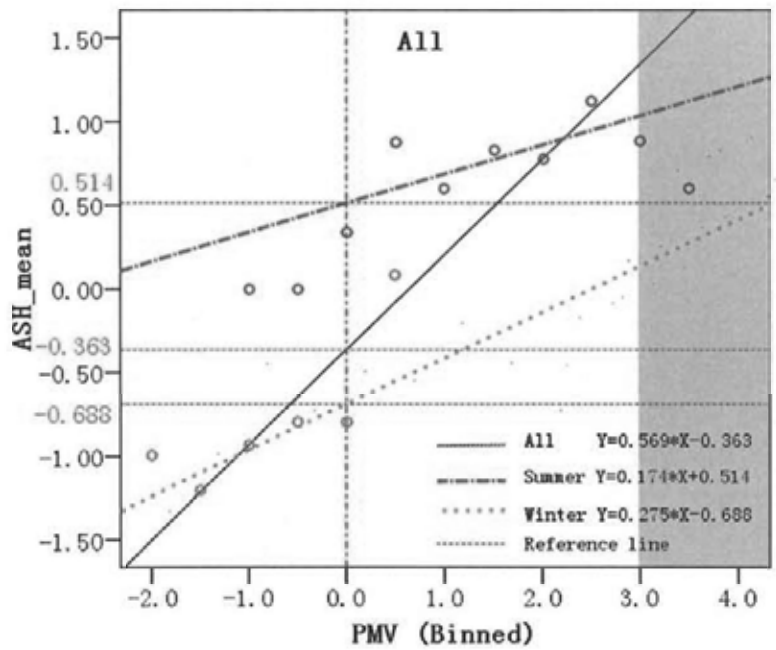


Figure5- 9: Seasonal difference of discrepancy between "ASH" and "PMV"

Additionally, Comparing with the separated season's results of "ASH" against on "PMV" (regression coefficient of "0.17"in summer and "0.275" in winter), extended PMV tool employing "0.569" expectancy factor still underestimates local residents' thermal adaptation in respective season as shown in Figure 5-9 (For these regressions, estimation error of "clo" and "met" are ignored here). The lower change rate "ASH" against on "PMV" in respective season proves the identified seasonal thermal adaptation. Additionally, the comparisons of acceptable thermal environments drawn from filed studies in China also repeat this seasonal variation displayed in above Table 5-4.

Therefore, extended PMV maybe can properly adjust the overall discrepancy between chamber studies and field studies, but its application for specific climate condition and specific population still need more verification. As Humphreys and Nicol noted: "*equations* *from empirical should not be extrapolated beyond the limits of the data from which they were derived*" (Humphreys and Nicol 2002).

Why are seasons different?

People adapting more easily to heat than they doing to cold probably results from more adaptive opportunities in hot environments compared with cold environments. In summer, adjustments of clothing, ventilation, space selection, food and drink, cooling devices, lower expectation, cool bathing, etc., are very efficient methods to avert thermal discomfort. While in winter, what the people frequently do is to change insulation, make more metabolic rate, minimize air movement, or have hot drink or food which have been taken account into PMV calculation, so the variation between "PMV" and "ASH" is much small in winter. This result is consistent with Zhang's result (Zhang, Wang et al. 2010).

Another reason maybe lies in the human's thermoreception and thermoregulation. Firstly, warmness receptor is deeper and less than coldness receptor on body surface area (Hensel 1981). Secondly, McIntyre concludes that cold sensation is more determined by mean skin temperature, while warm sensation depends initially on skin temperature hence on deep body temperature and warmth discomfort is dependent on skin wettedness (McIntyre 1980). Thirdly, the acclimatization in hot environment is much more significant in warm environment such as increased evaporation and blood volume (Lind and Bass 1963).

Additionally, the psychological adaptation is involved more in summer than in winter reported by local residents. Accompanying sweating in summer is very effective method to release inner heat when people ask themselves to be calm. Under this situation, sweating does not mean discomfort for the occupants, even sometime it means pleasure described as "piquant". While in winter, vasoconstrictions can not bring this kind of pleasure, although occupants can psychologically tolerate but physiologically suffer indeed, such as chilblain or getting a cold.

5.4 NON-THERMAL IMPACTS ON ADAPTIVE THERMAL COMFORT

As mentioned in the literature review chapter, achieving thermal comfort is shaped not only through physiological adaptation but also through psychosocial, behavioural and culture adaptation in the society. Non-thermal impacts probably influence occupants' adaptation ability to their corresponding thermal environments. This section will discuss those impacts from the view of occupants' living experience and thermal expectation, economic conditions and consumer-values, living habits and adaptive opportunities, based on the presented investigation results.

5.4.1 Living experiences and thermal expectation

"*The underlying hypothesis of the adaptive thermal comfort is that one's satisfaction with thermal environment is guided by adaptive adjustments (behavioural, physiological, and psychological) to not only the prevailing environmental conditions (outdoor climate), but to what we expect our indoor conditions to be*"(Kwok 1997). An expectation value was also employed by Fanger and Toftum to extend PMV's application in the naturally ventilated buildings. They classified expectation value into three categories depending on how common air-conditioned buildings were (Fanger and Toftum 2002). This can be understood as a kind of living experience which could influence occupants' thermal expectation. Enlightened by previous work, in the following discussion some tests are performed to check living experiences' impacts on residents' thermal expectation.

Here, thermal expectation is represented by the discrepancy between "Predicted Mean Vote (PMV)" and "Thermal Sensation Vote (ASH)", and the large discrepancy indicates low thermal expectation and small discrepancy indicates high thermal expectation. The thermal expectation may be attributable to living experiences shaped by housing characteristics (naturally ventilated vs. centrally air-conditioned), to a previous living background (local urban residents vs. new in-comers from country) and to location exposing to (indoor space vs. outdoor space[44]). Paired-sample T Tests and Pearson r are employed in this study to investigate the discrepancies between "PMV" and "ASH" and to explore the explanation ability of "PMV" on occupants' thermal sensation in real living environments. This is done by season, by housing characteristics, by previous living background and by location. The results of Paired-sample T test and bivariate-correlation testing for each group are displayed in Table 5-6.

Table5- 6: Paired-sample T test and bivariate-correlation testing by season, housing characteristics, previous living background and exposing location

Group Number	1	2	3	4	5	6	7
Season (Winter/Summer)	Winter	Winter	Winter	Summer	Winter	Winter	Summer
Housing characteristics (Centrally heated/Naturally ventilated)	Centrally heated	Naturally ventilated	Naturally ventilated	Naturally ventilated	Mixed	Naturally ventilated	--
Previous living background (Urban residents/in-comers from country)	Urban	Urban	Country	Urban	Urban	Mixed	Urban
Location (Indoor/Outdoor)	Indoor	Indoor	Indoor	Indoor	Indoor	Indoor	Outdoor
Sample size	42	212	107	301	254	319	416
Mean_ASH	0.714	-0.843	-0.271	0.851	-0.585	-0.651	1.34
Mean_PMV	-0.234	-0.569	-0.746	1.934	-0.514	-0.629	2.11
Mean discrepancy of ASH and PMV (ASH-PMV)	0.948	-0.274	0.475	-1.083	-0.071	0.022	-0.777
Discrepancy Sig.	0.000	0.000	0.000	0.000	0.282	0.658	0.000
Correlation between ASH and PMV Pearson r	0.078	0.164	0.405	0.168	0.254	0.139	0.411
Correlation Sig.	0.623	0.017	0.000	0.004	0.000	0.013	0.000

[44] The outdoor thermal comfort investigation data is derived from CHI's research project: "Physical Environments in the Existing Urban Housing Estate" under national 11-5 research project. The detailed information of this investigation refers to appendix 1.

It is found that for the investigated groups, except for groups of local urban residents in winter (Group 5) and naturally ventilated space in winter (Group 6), the "ASH" mean values are statistically significantly different from "PMV" value. All groups show a significantly positive correlation between ASH and PMV, except for the local urban residents in the centrally heated building group (Group 1).

5.4.1.1 Housing characteristics: naturally ventilated buildings vs. centrally heated buildings

In winter for local urban residents, "PMV" overestimated occupants' cool sensation in centrally heated room by "0.95" units (Group 1) and underestimates occupants' cool sensation in naturally ventilated room by "0.27" units (Group 2) (Indepentdent-Sample T test for "0.95" and "-0.27", $p<0.001$) . In the centrally heated room they reported feeling "slightly warm" in those environments calculated to be "slightly cool", while in the naturally ventilated rooms occupants reported a little cooler than PMV calculated. After merging these two groups into one group labelled 'local residents in winter' (Group 5), there is no statistically significant difference between "PMV" and "ASH", which repeats that the explanatory ability of "PMV" on "ASH" was different for naturally ventilated rooms and centrally heated rooms in winter for this case.

5.4.1.2 Living background: local urban residents vs. in-comer from country area

In winter in naturally ventilated buildings, "PMV" overestimated new in-comers' cool sensation by "0.48" unit (Group 3) and underestimates city local residents' cool sensation by "0.27" unit (Group 2) (Indepentdent-Sample T test for "0.48" and "-0.27", $p<0.001$). Similar to Group 5, for the merged group in winter in naturally ventilated buildings, no statistically significant difference between "PMV" and "ASH" could be found. This indicates that the explanatory ability of "PMV" on "ASH" is different for city local residents and new in-comers from country in winter.

5.4.1.3 Location: indoor space vs. outdoor space

Based on the comparison between the urban residents in naturally ventilated buildings (indoor) in summer group (Group 4), and the outdoor urban residents in summer group (Group 7), it is found that "PMV" overestimated the residents' warm sensation both in indoor thermal environments (by 1.08 units) and outdoor thermal environments (by "0.78" units), but the overestimation is more critical for indoor conditions (Indepentdent-Sample T test for "-1.08" and "-0.78", $p<0.001$). It displays that discrepancy between "PMV" and "ASH" is much bigger for indoor space comparing with outdoor space, which means indoor occupants have higher thermal expectation. It is consistence with the previous studies (Spagnolo and de Dear 2003; Junta Nakano 2004; Hwang and Lin 2007).

In summary, based on this study's results, housing characteristics, previous living background and whether people were indoors or outdoors had significant impacts on the occupants' thermal expectation, as defined. Despite climatic variation, occupants in naturally ventilated buildings had lower thermal expectation compared with those in centrally heated buildings; new in-comers from the country had lower thermal expectation compared with local urban residents; occupants in outdoor spaces had lower thermal expectations compared with occupants in indoor spaces.

5.4.2 Economic conditions and consumer-values

It is very natural to assume that wealthy people would demand environments close to thermal neutrality for comfort, while poor people would accept environments that were further from neutrality. For wealthy people have greater consuming capacity, and air-conditioning is not a considerable expense for them. However, based on the investigation of local residents' thermal adaptation and economic conditions, the assumption cannot be demonstrated.

In Investigation I, there was positive correlation between occupants' income and their maximal cooling/heating expense both in summer ($r=0.332$, $p<0.001$) and winter ($r=0.205$, $p=0.025$). However, the heating/cooling expense did not take into account the housing floor area in each family. Additionally, there was no statistically significant correlation between occupants' trigger temperature for switching on air-conditioning for summer-cooling and their family income ($r=0.063$, $p=0.283$); but a positive and significant correlation was found between occupants' trigger temperature for switching on air-conditioning for winter-heating with their family income ($r=0.200$, $p=0.029$). Meanwhile, the attitude to choosing heating/cooling methods also indicated that requirements for health and safety were much more important than economic efficiency (Table 4-6). These disparate results show no evident pattern linking income to comfort requirements directly.

The in-depth case studies in the winter indicated that consumer-values rather than economic conditions determine local residents' preference for thermal comfort. The husband from Family A said "I am just used to be frugal and I will not switch on air-conditioner when I feel ambient thermal environment is acceptable, even it is not perfectly thermal neutral". He also said, "when I carry on my work in the evening, I will prefer more thermal comfort and therefore switch on air-conditioner". The Family A actually is in the middle-class of the local residents and expense on air conditioning definitely is not a burden for them. It was similar for Family B. The wife told the interviewer that they had been used to this kind of indoor micro-climatic condition and they could accept it, although it might be conventionally quantified as "uncomfortable". The family members did not think neutral thermal comfort necessary and they were pleased to employ some simple adaptation behaviours to track with outdoor climatic variation. Money was not a big issue for Family B either. Family C was not the richest one in the investigation, yet they pursued almost neutral thermal comfort. The Mother in this family expressed her strong desire for a better living quality and she thought thermal comfort was important and also affordable, In short, underlying consumer-values had impacts on residents' choice about pursuing indoor thermal comfort. Based on the investigation results of present study, income is probably the key factor influencing consumer-values, but it was not a direct influencing factor for adaptive thermal comfort in this study.

As social psychologists have learned that the feeling of choice and control are important determinants of happiness and behaviour (Yates and Aronson 1983), occupants can achieve their thermal comfort and happiness if they can make their choices for themselves, whether through an adaptive or a static approach. consumer-values rather than income determines their choice.

5.4.3 Living habits and adaptive opportunities

Living habits relevant to thermal comfort are shaped by a combination of climate, housing characteristics, personality and social norms. Adaptive thermal comfort is a dynamic interaction process affected by those factors. The changing history of Americans from adaptive thermal comfort to static thermal comfort witnesses this interacting process towards a social norm of "air-conditioner as a indictor of middle class prestige", and the development of air-conditioning technologies providing "universal neutral thermal comfort" in building environments, as well as human's greed for cool comfort (Ackermann 2002). This study has investigated local residents' relevant living habits and the huge potential of adaptive thermal comfort has been found, but it is still too early to draw the conclusion that those living habits will prove to be enduring.

As suggested by Brager and de Dear in 1998, behavioural adjustments play a very important role in shaping occupants' adaptation, and they should be one of the research focuses in this area. For this study, the author emphasized the investigation of local residents' behavioural adjustments to thermal discomfort through questionnaires, observation and interview. The results showed that simple changes of occupants' behaviours were adopted widely to cope with thermal discomfort. They included ventilation control through windows and doors, changing clothes, changing the insulation of bed and chair, food and drink intake, and the use of heating/cooling equipment.

Table5- 7: Behaviours and adjustments to thermal discomfort

Basic thermal parameters	Residential behaviors and adjustments to discomfort	Architecture design strategies
Air temperature	Cooking, bathing, using heating/cooling equipments, electrical device, ventilation control through window and door;	Window/door design, heat transfer coefficient of building envelop, Pipe and ventilation system design
Radiation temperature	Basking, window shading; greenery;	Window/door design, balcony design, shading device, building orientation, building surface material and color, roof/wall greenery;
Occupants' metabolic rate	Food and drink intake, daily activities;	
Occupants' insulation	Changing clothes, changing insulation of bed and chair;	Floor material, furniture material;
Air velocity	Using fans, window/door control	Ceiling height, window/door design, layout, building configuration and surrounding wind environments;
Control ability on surrounding environments	Occupied space and time selection, control of windows/doors and heating/cooling equipments.	Layout, window/door design, heating/cooling system design;
Thermal expectation		Overall building thermal performance.

Behavioural adjustments can be categorized by the parameters influencing thermal load on human body and potential opportunities provided by building design strategies which are showed in Table 5-7 (Xiong and Tsou 2009). Main thermal parameters in dwelling are listed in the first column, corresponding residential behaviours and design strategies are listed in the second and third column. Most of those frequently used behaviours founded this investigation, no matter adjustments of occupants themselves or adjustments of surrounding environments do change the thermal load on human body and therefore release thermal discomfort. It indicates that these behavioural adjustments have been taken count into thermal sensation prediction based on thermal balance theory, and therefore the discrepancy of "PMV" and "ASH" should be explain rather than rational physiological and physical calculation. Psychological adaptation becomes the optional explanation.

5.5 WHAT IS THE AIM OF THERMAL ENVIRONMENT DESIGN FOR RESIDENTIAL BUILDINGS? ADAPTIVE THERMAL COMFORT OR STATIC THERMAL COMFORT?

Research interest in adaptive thermal comfort responded to the energy crisis in the mid-70s and initiated a new approach to study occupants' thermal comfort in the real building environments. Nobody can deny the notable achievements of thermal comfort studies in thermal chambers and their contributions to creating comfortable building environments. Maintaining heat balance between human body and ambient thermal environments is still a fundamental principle for practice engineers. However, if we look back to the evolution history of "Cool Comfort" in America (Ackermann 2002) and look at current China urban residents' "Adaptive Comfort" in both hot and cold environments, probably we can rethink our design purpose with regard to the thermal environment in the residential' buildings.

5.5.1 Performance and productivity

One reason for advocating air-conditioning in the work-place is its presumed contribution to working performance and productivity. However, whether physiological response to hot and cold stimulus, such as vasoconstriction, vasodilatation, shivering and sweating, etc.., will have effects on activity, performance or productivity depends upon the specific job or tasks of interest (Parsons 2003). In other words, subjects' expected goals in residential buildings determines whether those cognitive and manual performance change or distraction under cold or hot thermal environments will become constrains to achieve their goals or not.

For the residential behaviours in home, the traditional classification in architecture is based on the function model of lifestyle theory and normally called three-type methods (Takamasa 1984). The first type is to maintain life and physical needs of daily life, such as diet, sleep, excretion, sex; the second type is for supporting the first type behaviour, such as housework, production, consuming; the third type behaviour is for mental service, such as creation, game, representation, generation and so on. And the investigation of occupants' priority of preferred comfortable thermal environments for daily activities shows that "basic residential behaviour, such as sleeping, eating, excretion, etc." and "leisure, such as watching TV, listening music, chatting, etc." got highest votes, and "household work, such as cleaning, cooking, laundry, etc" got lowest votes. Actually, for some residential activities, the thermal requirement is not demanding, and sometimes the occupants even do not care the negative impacts from "thermal discomfort" and naturally can acceptable "discomfort" to certain extend. This is also one main reason of intermittent and local heating/cooling pattern are employed in home.

In short, for local residents' daily activities, neutral thermal comfort is not necessary in all the time and all the space in home. Residents can achieve general adaptive thermal comfort to satisfy their thermal needs.

5.5.2 Health and safety

The adaptively comfortable environments should be thermally within the safe boundary in terms of human body's physiological mechanism, especially for people who have very little adaptive opportunities. In extreme conditions of hypothermia and hyperthermia, clouding of consciousness, confusion, illness and collapse will have obvious implication. Fortunately, all the adaptively comfortable thermal environments published by different researchers today (Table 2-2, 2-3, 5-4) do not go beyond the damage thresholds. When healthy occupants are exposed to thermal environments within the temperature range from "14℃" to "27℃"with proper clothing and normal activities, they will be physiologically safe.

Additionally, slight heat stress and cold stress is helpful for human body to strengthen their thermoregulatory system. People exposed to neutral and static thermal environments for a long time could become addicted to those conditions and become less able to tolerate thermal diversity. Some residents even reported that they would like to tolerate some kind of discomfort because they want to train themselves to be stronger in facing various outdoor weather, rather than be fully dependent on indoor air-conditioning.

Certainly, adaptive thermal comfort definitely can guarantee occupants' physiological safety and sometimes it is even healthier for human body to survive in this climatically diverse world.

5.5.3 Comfort and pleasure

Thermal comfort is subjective state of mind that expresses "satisfaction with the thermal environment", and does not necessarily imply physical neutrality. Indeed, thermal pleasure can be perceived as peripheral cooling/warming that is likely to restore the core temperature to the set-point, such as cool breeze in warm environment and cold floor in warm environment.

Conventional "static" thermal comfort models (and associated standards) presume the body would prefer to maintain homeostasis with zero physiological thermoregulatory effort, i.e. zero regulatory sweating, zero thermogenesis, and zero vasoconstriction/vasodilatation. The adaptive comfort model (and associated standards) challenge the "zero thermoregulatory effort" presumption and brings the concept of "alliesthesia" which suggests zero thermoregulatory effort leads to thermal boredom (Cabanac 1971); but dynamic thermal stimulus in naturally ventilated buildings can initiate more thermal pleasure because of the compensating action in the so-called "uncomfortable environments".

Adaptive thermal comfort allows the transition through different thermal sensations. Especially a cooling stimulus in hot conditions or heating stimulus in cold conditions brings a lot pleasure in naturally ventilated environments. This kind of thermal pleasure arises from daily activities and can make delightful the residents' living experiences in their "dynamic home" more than in "neutral housing" (Heschong 1979).

5.5.4 Sustainability

Undoubtedly, one of main motivations for adaptive thermal comfort studies is to encourage more energy saving and more sustainable developments. If occupants can achieve "adaptive thermal comfort" with less energy, why do they need consume more energy for "static neutral thermal comfort"? Especially in current China urban environments, the energy demand in near future is so huge because of the fast urbanization process and big population base if static neutral thermal comfort is advocated. The investigation of local residents' adaptive thermal comfort has shown that occupants are very smart to adjust themselves and their surrounding environments to get comfort with little effort. Air-conditioning is one remedy for discomfort but not the only one. Jiang even argued that adaptive thermal comfort is more close to Chinese life-philosophy of harmony between human and nature (Jiang 2007). So, adaptive thermal comfort seems a more proper and sustainable approach for China urban housing design.

To sum up, adaptive thermal comfort can maintain safe, healthy and delightful daily life with less energy consumption in residential buildings and probably now is the right time to shift the thermal environment design aim from conventional neutral thermal comfort to adaptive thermal comfort.

5.6 Applications of Adaptive Thermal Comfort for Urban Housing Design

5.6.1 New thermal comfort standards and building energy consumption calculation

5.6.1.1 New thermal comfort standards establishment addressing adaptation

This study has presented evidence which found that local residents can achieve thermal comfort through adaptation under conditions which are classified as clearly "uncomfortable" according to existing thermal comfort standards. Adaptive thermal comfort is an innovative approach to help energy conservation and sustainable building development. However, in urban China, designers and engineers are still using existing standards without consideration of occupants' adaptation, and consequently huge unnecessary amounts of energy could be consumed in the near future. New thermal comfort standards addressing adaptation should be established in China as soon as possible[47].

As Nicol and Humphreys suggested "*the standard should help the designer make decisions about successful strategies in terms of the design of the building, the controls it provides and its service*" (Nicol and Humphreys 2002). Under current China urban housing environments, the new thermal standards addressing occupants' adaptation should cover three aspects: what indoor thermal environments are most likely to provide comfort, what is the range of acceptable environments, and what change-rate of indoor environment is acceptable?

Considering the implementation of standards, definiteness and simplicity are required. The existing thermal comfort standards specify the comfortable temperature range to guide building thermal environment design. The simplification from six thermal variables to one indicator makes the standards more applicable for designer as well as building occupants. However, the hidden assumptions of this simplification include that the other five thermal variables are fixed and constant, such as identical occupants with "0.5clo" clothing-level in summer and "1.0clo" in winter, accompanying "1.2met" activity; air movement's impact is ignored; humidity change coupling with temperature. But for the adaptive thermal comfort standard, those thermal variables inevitably will vary greatly with each other because of occupants diverse adaptation behaviours.

As mentioned in Section 2.4.2, the existing Design Standard for Energy Efficiency of Residential Building in Hot Summer and Cold Winter Zone (JCJ 134-2001) addresses category A as design goal (Table 2-5). For building energy calculations, the designed temperature is 26℃in summer and 18℃ in winter, with one 1/hour air change rate (The Ministry of Construction 2001).

[47] According to personal communication with Prof. Li Baizhan, the Chongqing University is conducting research work which would contribute new thermal standards for buildings addressing thermal adaptation.

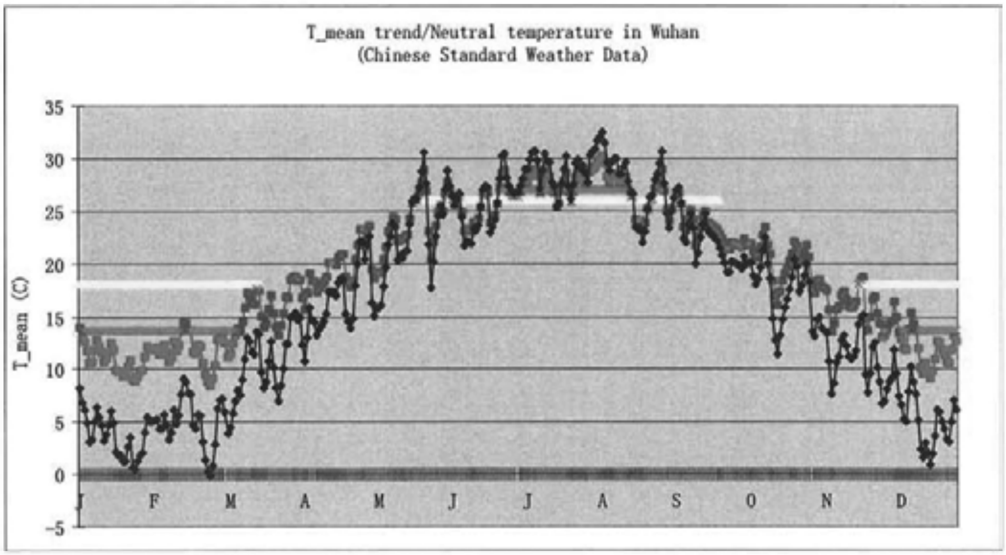
Fu's categories (Table 2-7) have taken into account the effects of humidity and air movements, which makes the temperature ranges from this standards and from field comparable. It can be found, for the category A, that the highest temperature 28℃ is a little higher than the upper limitation of acceptable temperature range of "14.0℃~27.0℃", and the lowest temperature "16℃" is higher compared with "14℃". The temperature range for category B is similar to acceptable ranges which fulfil the "thermal sensation" requirements (range of "11.1℃~31.8℃"). Therefore, there is possibility to update the standard to the more realistic highest or lowest temperature for adaptive thermal comfort.

The temperature range of "14℃~27℃" drawn from this study has considered the effects of humidity, air movement, occupants' clothing level and metabolic rate derived from this study. It indicates extrapolated application of this temperature range beyond the data limits in the HS&CW climatic zone is still controversial. As Hitchings mentioned, adaptive thermal comfort studies should address more contextually sensitive approaches; how the local climate, local occupants and local living habits shape how future thermal comfort will be understood and achieved is still much less than certain (Hitchings 2009).

5.6.1.2 More realistic building energy consumption calculation

Building energy consumption is a big issue in current China. Now, all the energy consumption calculation for heating/cooling still adopts old thermal comfort standards for building design, and the energy conservation potential from this calculation is not realistic. The fundamental assumption for estimating this potential is how much energy could be saved to achieve thermal comfort for new design building comparing with an imagined standard building of the 80's. China Statistic Bureau's data shows that China per capita building energy consumption has increased even though the building thermal performance has improved a lot. The total building energy consumption has increased 73% from 1997 to 2007 (Xiong and Tsou 2009). In other words, building energy consumption is not only related to the building thermal performance, but also highly associated with required comfort and with occupants' thermal behaviours.

The significant energy saving potential brought by more realistic thermal standards has been quantitatively demonstrated by some simulation (Henze, Pfafferott et al. 2007; Rijal, Tuohy et al. 2007; Toftum, Andersen et al. 2009) and qualitatively demonstrated by field investigations (Barlow and Fiala 2007; Pfafferott, Herkel et al. 2007). Figure 5-10 shows the comfortable temperature defined by different thermal standards for the whole year in Wuhan. It is found that the existing conventional thermal standard gives the most restricted comfortable temperature range, and the energy demand for maintaining comfort is the biggest (yellow line); while if the comfortable temperature is tracking outdoor temperature (green line) huge energy saving can be achieved, especially in winter. Additionally, residents' localized and intermittent heating/cooling patterns also reveal that homogeneous comfort is not necessary for naturally ventilated residential buildings. Therefore the further energy saving potential could be found if the behavioural factor is taken into consideration.



Blue line: Yearly Mean daily outdoor temperature based on Standard Weather Data in Wuhan;
Purple line: Neutral temperature with 0.5 Griffiths constant without temperature limitation;
Green lien: Neutral temperature with 0.5 Griffiths with comfortable temperature range of 14.0℃ to 27.0℃
Yellow line: Neutral temperature set by existing thermal standard.

Figure5- 10: Comfortable temperature defined by different thermal standards with the yearly outdoor temperature

5.6.2 Adaptive opportunities supplied by building design

Apart from more realistic energy consumption calculation, adaptive thermal comfort also appeals to urban housing design to provide more adaptive opportunities for occupants. User-oriented consideration is the key idea. The consideration should cover local climates as well local residents' living habits.

Table 5-7 has listed some building design strategies which can potentially provide adaptive opportunities for occupants to achieve their thermal comfort. In the following discussion, from the view of the planning and design, improvement suggestions on various scales will be carried out.

5.6.2.1 Urban scale

In any case of talking about thermal comfort, urban microcliamte must be taken into account because of its essentail relationship with building, city and occupants. When it comes to adaptive thermal comfort, some mertigation strategies could be applied in the urban scale.

5.6.2.1.1 Minimizing the urban heat island effect

Minimizing the heat island effect in the urban area is crucial for existing urban planing for better thermal enviornment. Firstly, proper distibution of developed lands and reserved lands plays an important role to avert urban heat acculumation. Further, the density also contributes to urban heat island effect and strict building (housing) denstity control must be emphasized. Additionally, modifying urban heat absorption and emission, using high-albido surfaces, increasing openness to allow cooling ventilation, etc., all have the potential to improve the urban microclimate.

5.6.2.1.2 Utilization of good natural resources

Housing planning in Wuhan should seriously consider how to utilize the good natural resources to supply more "Urban Green Lung" for this city. Rivers, lakes and mountains can create a lot of comfortable outdoor space for residents to avert their discomfort from building blocks, by providing better thermal environments and psychological relaxation.

5.6.2.2 Community scale

Encouraging more outdoor activities in the community is not only beneficial to residents' communication but also to comfort acquisition. Thermally comfortable outdoor and semi-outdoor space design should put more attention on following aspects.

5.6.2.2.1 Building layout and building configuration optimization

Building layout and building configuration affect outdoor ventilation and sunshading greatly. In Hot-summer and Cold-winter climatic condition, the outdoor space under shadow with breeze is preferred by residents in summer. However, in winter, residents will enjoy windless outdoor space with direct sunlignt. Therefore, optimization of buildingy layout and building configuration must carefully think about not only local climatic characteristics including prevailing wind direction, wind velocity and local solar altitude, but also residents' rountines of outdoor space ulilization, such as when and where they would like occupy.

5.6.2.2.2 Greenary, shelters and facilities

Greenary is very effective stategy to creat thermally comfortable outdoor space, espacially in summer, because of its shadow, lower surface temperature of leafs and more psychological cooling effect from plants. Defoliate plants are recommendated to response the local HS&CW climate. Meanwhile, shelters and good facilities for outdoor activiity are also very important to attact residents to join in the communitiy, such as chairs, pergola, exerciser and footpath, etc. The foundamental idea of creating outdoor space is gurantee the comfort and attaction.

5.6.2.3 Housing scale

The double challenges in HS&CW climate determine the flexibility and diversity of design strategies on the housing scale to contribute more adaptive opportunities for occupants. Maximizing control-ability of occupants in their living environment is the key idea and the following strategies probably could give some inspiration.

5.6.2.3.1 Maximizing solar radiation in winter but minimizing it in summer

Solar radiation in winter can greatly improve thermal environment and the living habits investigation also showed that local residents enjoyed basking on the balcony. Meanwhile, the solar radiation in summer through windows and on external walls also heats up the indoor space, and local residents reported that they liked to use heavy curtains and additional shading to obstruct sunlight in summer, especially from the west. Therefore, some strategies, such as external adjustable shading devices, glass-enclosed balconies, green-roofs and vertical greenery are very useful to meet occupants' contrary requirements in the different season.

5.6.2.3.2 Maximize ventilation in summer

In the hot-humid summer, ventilation is one effective way to reduce thermal discomfort. Operable windows, indoor layout beneficial to cross ventilation and enough ceiling height for a ceiling fan all are potential design strategies for maximizing ventilation in residential buildings. This study has shown that even most of the investigated housing units had the potential for natural ventilation. The indoor air velocity was very low because of insufficient outdoor wind, and so the outdoor ventilation environment is crucial for the indoor natural ventilation. Therefore the factors of building site, prevailing wind direction and surrounding buildings should be investigated and brought into the design process.

5.6.2.3.3 Flexible heating/cooling system

The investigation in this study shows that local residents prefer individually controlled air-conditioners reflecting the local climate. Actually, this kind of heating/cooling method is very energy efficient and its per capita energy consumption is much lower compared with a central heating/cooing system (Jiang 2007; Xiong and Tsou 2009). Based on the huge population in HS&CW zone and its climatic characteristics, this flexible control heating/cooling system is the best solution in residential buildings. Central air-conditioning is still controversial and its popularizing should not be encouraged too much.

To sum up, the design strategies on the urban and community scale focus on creating comfortable outdoor space and encouraging more its utilization; design strategies in the housing scale emphasize providing more controllability and opportunities for occupants to adjust themselves or surroundings to achieve their adaptive thermal comfort with minimum energy cost.

CHAPTER 6

CONCLUSIONS

The present study investigated local residents' adaptive thermal comfort in a Hot-Summer and Cold-Winter climatic zone (Wuhan) within China urban housing environments. The investigation focused on local residents' thermal behaviours in daily life and their real thermal perception in naturally ventilated buildings both in winter and summer. More realistic acceptable thermal boundaries for local residents, addressing adaptation, have been drawn, and an implementable adaptation model is suggested for residential buildings in a hot-humid and cold-damp climate. Through broad discussion, the thesis also identifies some general problems of adaptive thermal comfort studies including thermal sensitivity and thermal neutrality, non-thermal impacts, application-extension of the existing thermal indices' to adaptive thermal comfort, and adaptive opportunities supplied by building design.

6.1 SUMMARY OF CONCLUSIONS

The most significant conclusion from this study is that local residents in the studied Hot-Summer and Cold-Winter climatic zone (Wuhan) could achieve thermal comfort through adaptation under conditions which are classified as clearly "uncomfortable" according existing thermal comfort standards. This fact of residents' adaptive thermal comfort offers great opportunity for more energy-saving housing design. This chapter brings together the key findings drawn from this study as follows.

1. Local residents' thermal behaviours were well-adapted to HS&CW climate through many kinds of convenient and simply adjustments including dressing

habits, control of windows and doors, food and drink intake, intermittent and local heating/cooling patterns and lower thermal expectation.

2. In the naturally ventilated residential buildings, the measured indoor thermal environments were very hot-humid in summer and cold-damp in winter, and were highly associated with outdoor climate. Occupants reported general acceptance and comfort in those conditions but would have preferred to be cooler in summer and warmer in winter.

3. For the majority of local residents with regard to thermal adaptation in naturally ventilated residential buildings, an acceptable operative temperature range was suggested as 14.0℃ to 27.0℃ which was applicable to relative humidity range from 10% to 87%.

4. Under Hot-Summer and Cold-Winter climatic conditions, an adaptive thermal comfort model, relating the indoor temperature for comfort (Tc, ℃) to the prevailing mean outdoor temperature (Tout, ℃), was suggested as "Tc=0.6Tout+9.8", with comfortable temperature range of "14℃" to "27℃". It would be feasible to employ this relation in new thermal comfort standards contributing building energy conservation.

5. Local residents' thermal sensitivity and thermal neutrality in real living environments were consistent with those found in international adaptive thermal comfort studies from the view of whole year, while local residents' thermal adaptive ability was unusually high. The possible reasons came from seasonal climatic variation as well as non-thermal factors including their thermal expectation, consumer-values and living habits.

6. Conventional thermal indices such as "PMV" and "SET" overestimated local residents' thermal sensitivity in the real living environments, but they were still useful thermal environment evaluation tools to predict occupants' adaptive thermal comfort and thermal neutral, after some modification from adding an expectation value.

7. Occupied building characteristics, occupants' previous living background and locations exposing to influenced occupants' thermal expectation and comfort achievement. Consumer-values and living habits also altered how and to what extend residents could adapt.

8. In China today, adaptive thermal comfort could support a safe, healthy and delightful daily life with less energy consumption in residential buildings, and now is the crucial time to encourage design strategies that provide more adaptive opportunities for occupants on urban, community and housing scales.

6.2 Research Contributions and Limitations

The main body of this thesis presents the investigation methods and research results focusing on adaptive thermal comfort in residential buildings in the hot-humid summer as well as the cold-damp winter in Wuhan. Most important original contributions of this study are follows:

- Theoretically, the thermal behaviour investigation conducted in this study provide one systematic way to understand adaptive thermal comfort in real living environments, and the research results provide an implementable adaptation model and acceptable temperature and humidity range for the localized climatic conditions and housing environments, which can contribute to form new thermal comfort standards for potential building energy conservation;

- Methodologically, this thesis provides a broader database for general adaptive thermal comfort studies, especially in cold environments. It helps to verify the feasibility of employed research methods in the field of residential buildings, in terms of application and extension of existing thermal indices, operation mechanisms of adaptive thermal comfort under thermal and non-thermal impacts, and feasible building design strategies promoting more adaptive opportunities.

Apart from the general limitations of the field-study research method and associated statistics, as discussed in section 1.5, some limitations exist on the data analysis and results interpretation in this study as follows:

- Achieving adaptive thermal comfort is a dynamic process between the human body, thermal stimulus and non-thermal impacts. This study considers only those factors mentioned in the questionnaires and certain selected physical characteristics in residential buildings in Wuhan. It is possible that information uncollected in this study may have significant impacts on occupants' adaptive thermal contort achieving.

- The research was conducted with a small sample size in Wuhan, and it resulted in some difficulties of quantitative analysis for specific variables between different groups, such as varied humidity groups, varied air velocity groups, varied age and housing income groups.

Some of these limitations are beyond the research framework set for this thesis. Most of the remaining concerns will be developed in further investigation work. However, this empirical study's results are based on the collected data. Due to the constraints of time and resources, a non-probability sampling method (accessibility sampling) was employed in this study, and therefore one should be cautious if generalizing the statistical findings from this study to other populations, locations and building types.

6.3 Further Research

Work on adaptive thermal comfort in the Hot-Summer and Cold-Winter climatic zone may be expanded in a number of ways. Four suggestions for further research emerge from this project.

1. Humidity impacts in cold environments

The heat balance model shows the humidity's impacts on thermal comfort under hot conditions. The high moisture content restrains the evaporation heat transfer from the skin surface (ASHRAE 2005). Generally, people feel warmer in higher humidity environments, keeping other five thermal parameters the same, as clearly displayed by Gagge's diagrams, even in cold conditions (Gagge, Fobelets et al. 1986). However, during the investigation in this study, many residents reported their cold discomfort coming from a "clammy" feeling with high humidity and low temperature. In other words, higher humidity in cold environment probably makes local residents feel colder comparing with lower humidity in the field. However, the humidity variation within same temperature group was small and no significant effect could be found in this study. Therefore, the author encourages more studies comparing the effects of different humidities in cold environments, in the field as well as in the thermal chamber.

2. Seasonal difference of adaptive thermal comfort in Hot-Summer and Cold-Winter climatic conditions

The twin climate challenge of summer heat and a winter cold complicates the study of adaptive thermal comfort in the Hot-Summer and Cold-Winter area. Although some similarity between adaptive behaviours in the two seasons has been found in this study, uncertainties exist in the seasonal differences, such as what are the different adaptively comfortable thermal boundaries in each season. Therefore, more comprehensive field studies are required to understand the seasonal difference of local residents' adaptive thermal comfort, including different adaptive behaviours, different adaptive ability, different adaptively comfortable thermal boundaries, and different operation mechanism of the human body corresponding to opposite thermal stimuli. Investigations in autumn and spring are desirable in future to draw more sophisticated conclusions from the study of climatic conditions.

3. Adaptive thermal comfort studies focusing on in-comers from country area

China is going through rapid urbanization and several hundred million people will move from country to urban regions. The change of life style will influence their thermal requirements in the daily life and a tremendous energy demand is foreseen. Adaptive thermal comfort studies focusing on in-comers from country area will play a vital role for China building energy conservation in the near future. In this study, even very limited data from in-comers have shown that they have a lower expectation of thermal comfort. But questions remain. What are their thermal requirements in the urban life? Doe any adaptive ability difference exist between in-comers and local residents? What kind of thermal environments are comfortable for them allowing for adaptation? What kind of adaptive opportunities could be provided by housing design for these in-comers?

4. Potential building energy conservation and sustainable housing design strategies

Numerical calculation and simulation of energy conservation resulting from adaptive thermal comfort and associated thermal standards could be conducted in future work. Although this thesis has proposed some housing design strategies contributing more adaptive opportunities for occupants, their effects and feasibility need more verification, and post-occupancy evaluation is one possible approach.

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APPENDIX

Appendix A: Variable Name and Coding Conventions in the Field Work

Variable's Code Name	Description of Variable and Units
Outdoor Thermal Condition (from observatory)	
day15_ta	outdoor 3pm (max) air temp on day of survey [℃]
day06_ta	outdoor 6am (min) air temp on day of survey [℃]
dayav_ta	outdoor average of min/max air temp on day of survey [℃]
day15_rh	outdoor 3pm (min) relative humid on day of survey [%]
day06_rh	outdoor 6am (max) relative humid on day of survey [%]
dayav_rh	outdoor average min/max relative humid on day of survey [%]
Trm	Running mean of outdoor temperature weighted according to their distance in the past using (1*Ttoday+0.8*Tyesterday+0.4*Tday-before-yesterday+0.2*Tday-before-day-before-yesterday)/2.4
Outdoor Climate measurements (near the measured indoor space)	
OTA	air temperature [℃]
OVE	air speed [m/s]
ORH	relative humidity [%]
Indoor Thermal Condition	
TA	air temperature [℃] (seated subject at 0.6m height, standing subject at 1.1m height)
TG	globe temperature [℃] (seated subject at 0.6m height, standing subject at 1.1m height)
VEL	air speed [m/s] (seated subject at 0.6m height, standing subject at 1.1m height)
RH	relative humidity [%]
Calculated Thermal Indices	
TR	radiation temperature [℃]
TOP	operative temperature [℃]
ET	new effective temperature index ET [℃]
SET	new standard effective temperature index SET [℃]
PMV	Predicted Mean Vote, Fanger's Model [-3, +3]
PPD	Predicted Percentage Dissatisfied, Fanger's Model [%]
Subjective Thermal Perception	
AC	thermal experience in the last 15 minutes [1=been in air-conditioned space, 0=not been in air-conditioned space]
ASH	ASHRAE Thermal Sensation Scale [-3, 0,+3]
HUS	humidity sensation [1(too damp), 5(too dry)]
AMS	air movement sensation [1(too still), 5(too windy)]
COMF	general thermal comfort right now [0= comfortable, 3=very uncomfortable]
MCI	thermal Preference [1=want warmer, 2=no change, 3=want cooler]
TSA	thermal Acceptability [0=acceptable, 3=extremely unacceptable]
ACT10	metabolic activity in last 10 minutes [met]
ACT20	metabolic activity between 20 and 10 minutes ago [met]
ACT30	metabolic activity between 30 and 20 minutes ago [met]
ACT60	metabolic activity between 60 and 30 minutes ago [met]

MET	average metabolic rate of subject [met]
CLO	ensemble clothing insulation [clo]
UPHOLST	insulation of the subject's chair [clo]
INSUL	clothing plus upholstery insulation [clo]
Daily Thermal Behaviors	
FBA	Frequency of behavioral adjustments (winter/summer)
FBA1	Closing/opening doors [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA2	Closing/opening windows [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA3	Increasing/decreasing clothing [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA4	Increasing/decreasing chair or bed's insulation [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA5	Hot/cold food and drink [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA6	Using heater/fans [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA7	Switching on air-conditioner for heating/cooling [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA8	Portable heat source/swimming and cool shower[1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA9	Basking in the sunshine/keeping calm [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA10	Usage of warmer/cooler space [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA11	Fix heat source/ adjusting thermostat [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA12	Improving building thermal performance [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA13	Increase/reducing activities [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA14	Reducing outdoor activities/vegetation cooling [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA15	Changing sleep habits/evaporation cooling [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA16	Body posture/walking out in the evening [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA17	Hot (foot)bath/sleeping outside [1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
FBA18	Lower thermal expectation[1=never, 2=rarely, 3=sometimes, 4=often, 5=always]
Basic Identifiers, Demographics and Personal Non-Climatic Variation	
BLCODE	building ID code
SUB	subject number
AGE	subject's age [years]
SEX	subject's gender [1=male, 0=female]
HEAL	subject's health conditions [0=healthy, 1=unhealthy]
CAR	subject's career
STIVE	Average time stay in home of subject
YEAR	year
DAY	julian date [jan 1=1, dec 31=365] (23th, July=207)
TIME	time [24hours]
INCOME	Family's income [RMB]
EXPENSE	Average expense on heating/cooling [RMB]

Notes: The coding is modified on the basis of de Dear and Brager's work.

Source: de Dear, R., G. S. Brager, et al. (1997). Developing an adaptive model of thermal comfort and preference. Sydney & Berkeley, Macquarie Research Ltd., Macquarie University & Center for Environmental Design Research, University of California

Appendix B: Garment Insulation Values

Garment Description[a]	$I_{clu,i}$, clo[b]
Underwear	
Men's briefs	0.04
Panties	0.03
Bra	0.01
T-shirt	0.08
Full slip	0.16
Half slip	0.14
Long underwear top	0.20
Long underwear bottoms	0.15
Footwear	
Ankle-length athletic socks	0.02
Calf-length socks	0.03
Knee socks (thick)	0.06
Panty hose	0.02
Sandals/thongs	0.02
Slippers (quilted, pile-lined)	0.03
Boots	0.10
Shirts and Blouses	
Sleeveless, scoop-neck blouse	0.12
Short-sleeved, dress shirt	0.19
Long-sleeved, dress shirt	0.25
Long-sleeved, flannel shirt	0.34
Short-sleeved, knit sport shirt	0.17
Long-sleeved, sweat shirt	0.34
Trousers and Coveralls	
Short shorts	0.06
Walking shorts	0.08
Straight trousers (thin)	0.15
Straight trousers (thick)	0.24
Sweatpants	0.28
Overalls	0.30
Coveralls	0.49
Suit jackets and vests (lined)	
Single-breasted (thin)	0.36
Single-breasted (thick)	0.44
Double-breasted (thin)	0.42
Double-breasted (thick)	0.48
Sleeveless vest (thin)	0.10
Sleeveless vest (thick)	0.17
Sweaters	
Sleeveless vest (thin)	0.13
Sleeveless vest (thick)	0.22
Long-sleeved (thin)	0.25
Long-sleeved (thick)	0.36

Dresses and skirts[c]	
Skirt (thin)	0.14
Skirt (thick)	0.23
Long-sleeved shirtdress (thin)	0.33
Long-sleeved shirtdress (thick)	0.47
Short-sleeved shirtdress (thin)	0.29
Sleeveless, scoop neck (thin)	0.23
Sleeveless, scoop neck (thick)	0.27
Sleepwear and Robes	
Sleeveless, short gown (thin)	0.18
Sleeveless, long gown (thin)	0.20
Short-sleeved hospital gown	0.31
Long-sleeved, long gown (thick)	0.46
Long-sleeved pajamas (thick)	0.57
Short-sleeved pajamas (thin)	0.42
Long-sleeved, long wrap robe (thick)	0.69
Long-sleeved, short wrap robe (thick)	0.48
Short-sleeved, short robe (thin)	0.34
[a]"Thin" garments are summerweight; "thick" garments are winterweight [b]1 lclo = 0.88°F·ft²·h/Btu [c]Knee-length	

Source: ASHRAE (2005). Chapter 8: Thermal Comfort. ASHRAE Handbook of Fundamentals (de Dear, Brager et al. 1997)

Appendix C: Typical Metabolic Heat Generation for Various Activities

	Btu/h·ft^2	met[*]
Resting		
Sleeping	13	0.7
Reclining	15	0.8
Seated, quiet	18	1.0
Standing, relaxed	22	1.2
Walking (on level surface)		
2.9 fps (2 mph)	37	2.0
4.4 fps (3 mph)	48	2.6
5.9 fps (4 mph)	70	3.8
Office Activities		
Reading, seated	18	1.0
Writing	18	1.0
Typing	20	1.1
Filing, seated	22	1.2
Filing, standing	26	1.4
Walking about	31	1.7
Lifting/packing	39	2.1
Driving/Flying		
Car	18 to 37	1.0 to 2.0
Aircraft, routine	22	1.2
Aircraft, instrument landing	33	1.8
Aircraft, combat	44	2.4
Heavy vehicle	59	3.2
Miscellaneous Occupational Activities		
Cooking	29 to 37	1.6 to 2.0
Housecleaning	37 to 63	2.0 to 3.4
Seated, heavy limb movement	41	2.2
Machine work		
sawing (table saw)	33	1.8
light (electrical industry)	37 to 44	2.0 to 2.4
heavy	74	4.0
Handling 110 lb bags	74	4.0
Pick and shovel work	74 to 88	4.0 to 4.8
Miscellaneous Leisure Activities		
Dancing, social	44 to 81	2.4 to 4.4
Calisthenics/exercise	55 to 74	3.0 to 4.0
Tennis, singles	66 to 74	3.6 to 4.0
Basketball	90 to 140	5.0 to 7.6
Wrestling, competitive	130 to 160	7.0 to 8.7
[*]1 met = 18.4 Btu/h·ft^2		

Source: ASHRAE (2005). Chapter 8: Thermal Comfort. ASHRAE Handbook of Fundamentals

Appendix D: Comparison of Hourly Climatic Data between Measuring dates and Wuhan's Standard Weather Data in the Same Periods

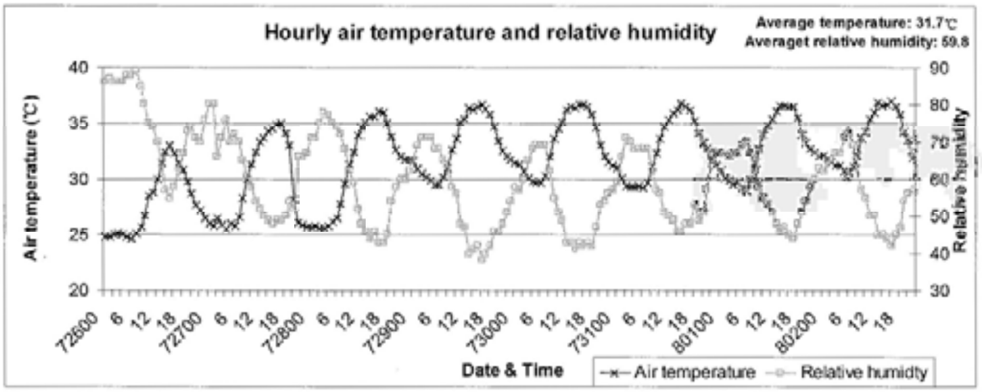


Figure d-1: Hourly air temperature and relative humidity measured in 2007 summer

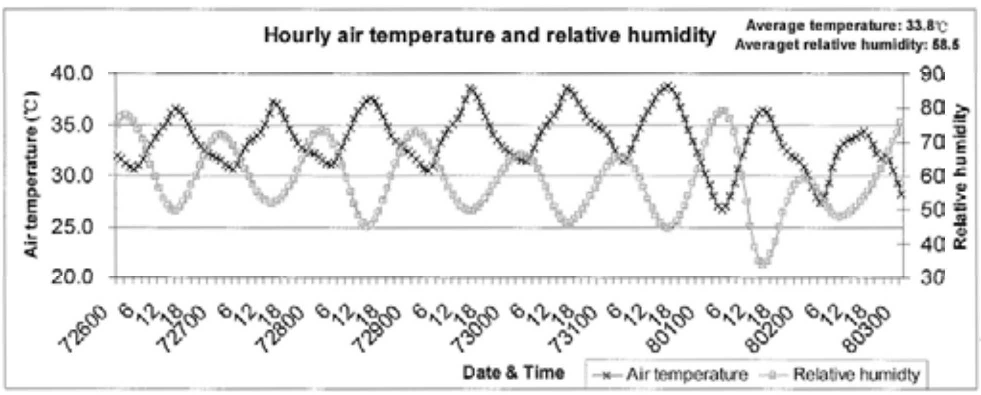


Figure d-2: Hourly air temperature and relative humidity in the same period of Standard Weather Data

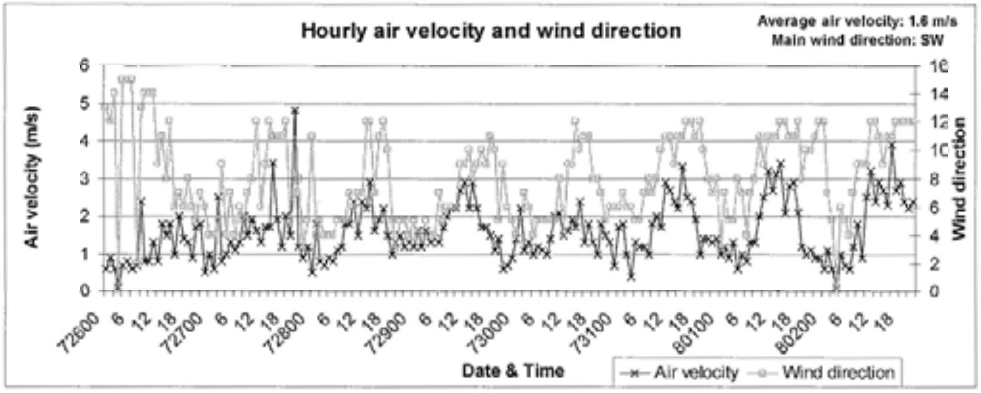
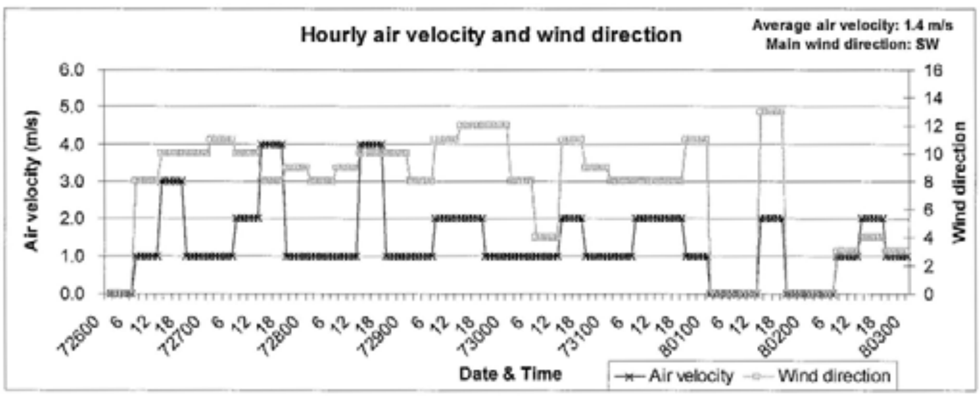


Figure d-3: Hourly air velocity and wind direction measured in 2007 summer



(Wind direction: 0-N, 1-NNE, 2-NE, 3-ENE, 4-E, 5-ESE, 6-SE, 7-SSE, 8-S, 9-SSW, 10-SW, 11-WSW, 12-W, 13-WNW, 14-NW, 15-NNW, 16-No wind)

Figure d-4: Hourly air velocity and wind direction in the same period of Standard Weather Data

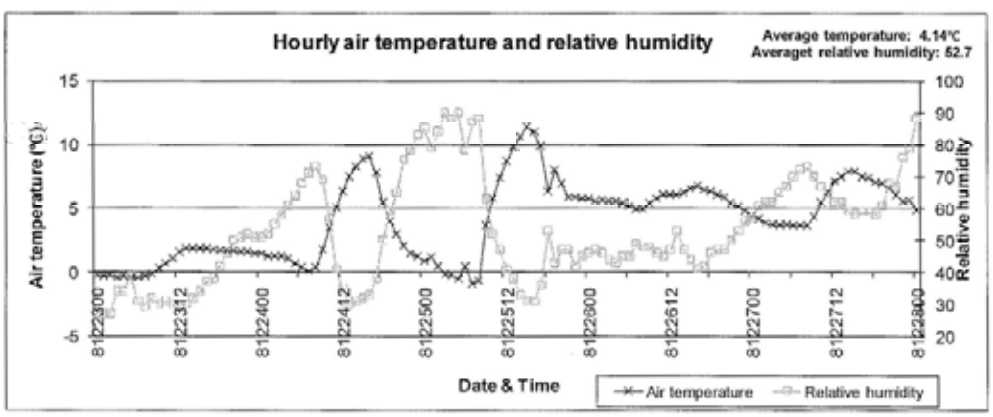


Figure d-5: Hourly air temperature and relative humidity measured in 2008 winter

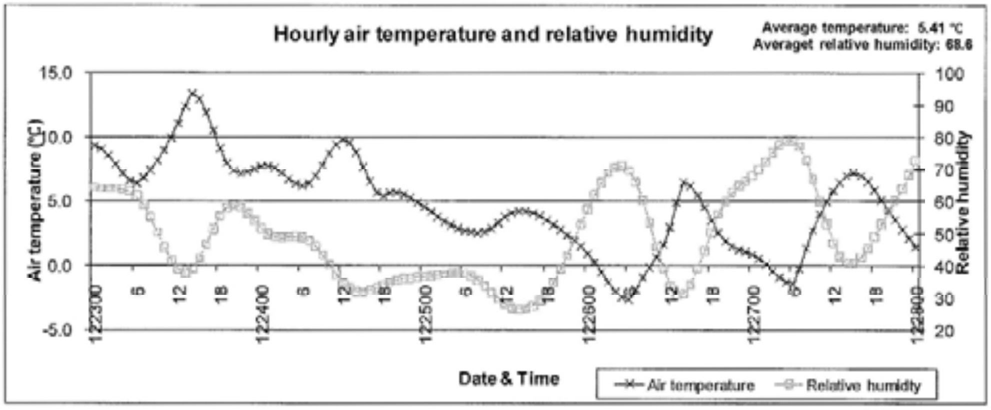


Figure d-6: Hourly air temperature and relative humidity in the same period of Standard Weather Data

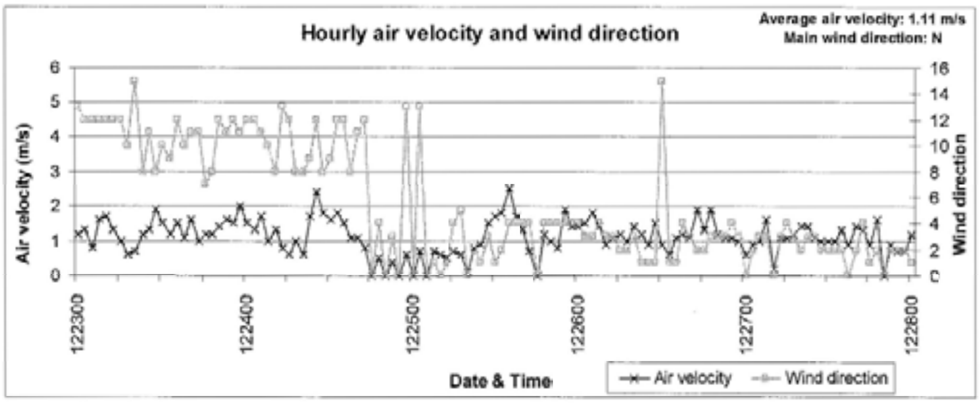


Figure d-7: Hourly air velocity and wind direction measured in 2008 winter

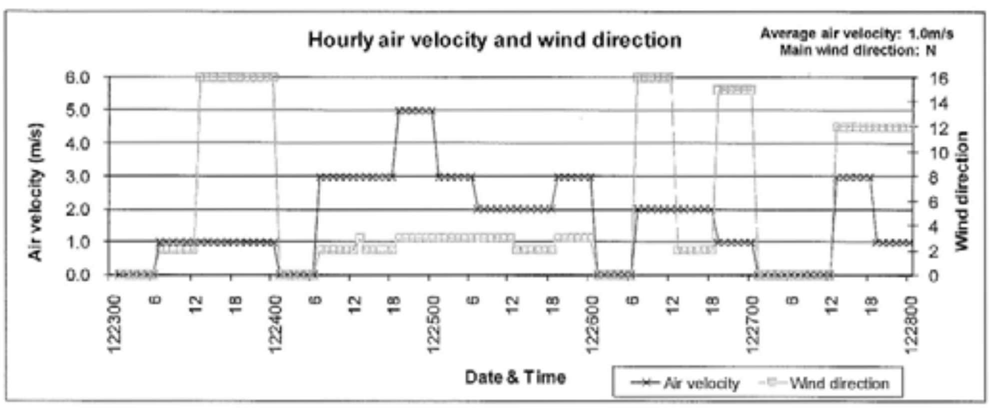


Figure d-8: Hourly air velocity and wind direction in the same period of Standard Weather Data

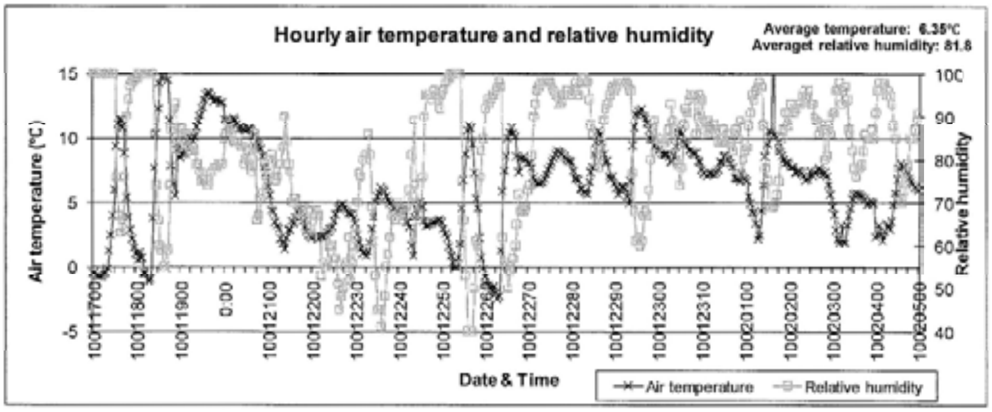


Figure d-9: Hourly air temperature and relative humidity measured in 2010 winter

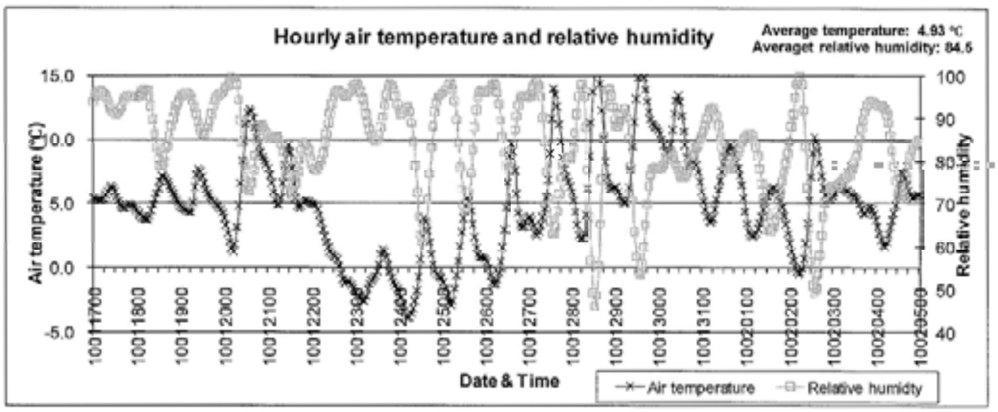


Figure d-10: Hourly air temperature and relative humidity in the same period of Standard Weather Data

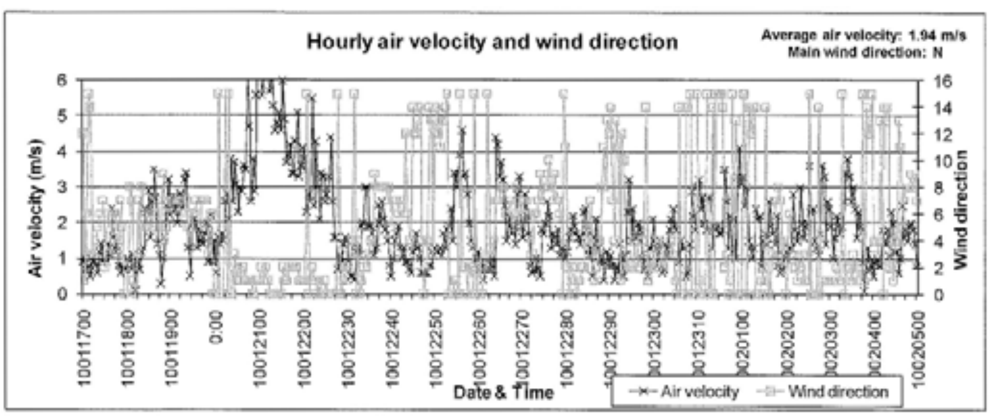


Figure d-11: Hourly air velocity and wind direction measured in 2010 winter

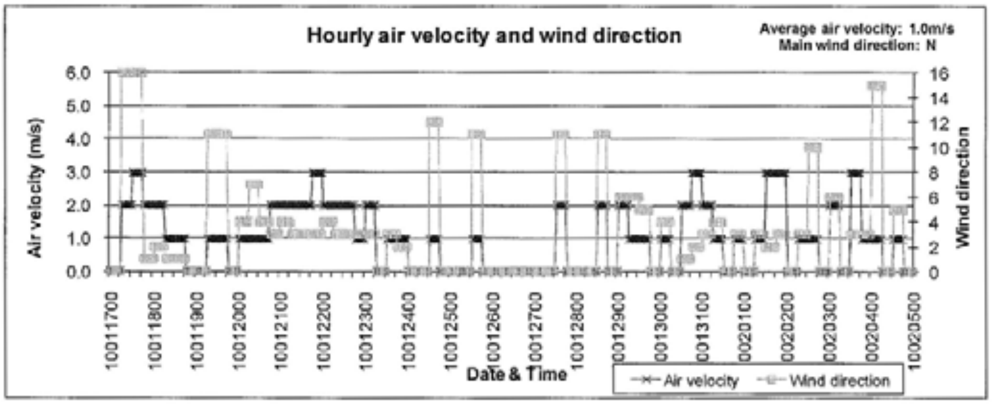


Figure d-12: Hourly air velocity and wind direction in the same period of Standard Weather Data

Measuring data source: Automatic Hubei Observatory

Website: http://zdz.hbqx.gov.cn/zhindex.php?sc=2007080300

Wuhan's Standard Weather Data source: National Meteorological Information Center, C. M. A. and T. U. Department of Building Science (2005). Special Meteorological Data for Building Thermal Environment Analysis in China. Beijing, China Architecture and Building Press.

Appendix E1: Questionnaire A for Investigation I (Summer & Chinese Version)

Survey of Residents' Thermal Adaptation in the Hot-Sumer and Cold-Winter Region of China (summer)

This is a research project commissioned under the Center for Housing Innovations of the Chinese University of Hong Kong, which aims to identify the thermal adaptation of local residents in the Hot-summer and Cold-winter climatic zone of China. In order to have broad and objective findings, we sincerely invite you to this research and your answers will contribute to thermal comfort study and thermal environmental estimation in this climatic region.

The collected information will be treated **confidentially** and only used for research work. For enquiries and information, please contact Ms. XIONG Yan. Email: xiongyan@cuhk.edu.hk Tel: 852-9257665 Fax: 852-26036515

BACKGROUND INFORMATION

1. How many years have you lived in the climatic region of Hot-summer and Cold-winter in China, such as cities of Wuhan, Shanghai, Chongqing, Nanjing, Hangzhou, Changsha, etc.?______
   a, less than 1 year b, 1~3 years c, 4~6 years d, 8~12 years e, 12~20 years f, more than 20 years

2. What is the "gross floor area" of your house/apartment? _____ And how about the following room number? (please tick the circle corresponding to right number)
   a, less than 30 sqm b, 30~60 sqm c, 61~90 sqm d, 91~120 sqm e, 121~200 sqm f, more than 200 sqm

	0	1	2	3	4 or more
3. Bedroom + reading room number	○	○	○	○	○
4. Living room + dining room number	○	○	○	○	○
5. Bathroom number	○	○	○	○	○
6. Kitchen number	○	○	○	○	○
7. Balcony number	○	○	○	○	○

8. What kind of building type is your house/apartment? ____
   a, low-storey dwelling (1~3 storey)
   b, multi-storey dwelling (4~6 storey)
   c, Middle and high-storey dwelling (7~9 storey)
   d, High-storey dwelling (10 and more than 10 storey)

9. How many generations are living together in your house/apartment? ____
   a, 1 b, 2 c, 3 d, 4 and more than 4

10. How many people are living in your house/apartment permanently now? ____
   a, 1~2 b,3~4 c, 5~6 d, 7 and more than 7

11. How many hours do you stay in home per day on average? ____
   a, less than 6 hours b, 6~10 hours c, 10~14 hours d, 14~18 hours e, 18~24 hours

12. How many hours do your families stay in home per day on average? (if no families, please ignore this question) ____
   a, less than 6 hours b, 6~10 hours c, 10~14 hours d, 14~18 hours e, 18~24 hours

13. What type of air-condition do you use in your house/apartment? ____

a, no air-condition b, individual control air-condition c, central control air-condition d, hybrid of b&c

14. What kind of additional cooling equipments do you use in your house/apartment except of air-condition? ____
    a, no other equipment b, mechanical fan c, mechanical cooling fan d, others

15. Generally, how do you control your air-conditions in terms of space? ____
    a, switch on them just in one room
    b, switch on them in several rooms
    c, switch on them in all the rooms

16. Generally, how do you control your air-conditions in terms of time? ____
    a, switch on them when you need and switch off them when you do not need
    b, switch on them when you need and keep them on for a while even you do not need them really
    c, switch on them all day

RESPONSE TO HOT ENVIRONMENTS

17. In the daytime of summer, what kind of windows & doors do you like to keep open? (multiple-choice question)____
    a, all of them
    b, windows & doors of balcony
    c, windows & doors of kitchen and bathroom
    d, windows & doors of bedroom and reading room
    e, windows & doors of living room and dinning room
    f, non of them

18. In the daytime of summer, when the temperature increase to ____°C, you will switch on air-condition?
    a, less than 22 °C b, 22 °C c, 25°C d, 28 °C
    e, 32 °C f, 35 °C g, 38 °C h, 42 °C
19. In the nighttime of summer, when the temperature increase to ____°C, you will switch on air-condition?
    a, less than 22 °C b, 22 °C c, 25°C d, 28 °C
    e, 32 °C f, 35 °C g, 38 °C h, 42 °C
20. Which following periods of time do you like to switch on air-conditions during? (multiple-choice question) ___
    a, never b, 6:00~9:00 c, 9:00~12:00 d, 12:00~15:00 e, 15:00~18:00
    f, 18:00~20:00 g, 20:00~23:00 h, 23:00~2:00 i, 2:00~6:00

21. Why kind of daily activities' quality do you want to maintain mostly through switching on air-conditions? (multiple-choice question) ____
    a, basic residential behavior, such as sleeping, eating, excretion, etc.
    b, household work, such as cleaning, cooking, laundry, etc
    c, taking care of children, elders or disable families
    d, leisure, such as watching TV, listening music, chatting, etc.
    e, social activities, such as entertaining friends, family gathering, meeting, etc.
    f, working or studying

22. What is your dressing habit in home in summer? Tops____Trousers____ Shoes____

Top:	a, naked	b, bra/vest	c, thin short-sleeves
	d, thin long-sleeves	e, thick short-sleeves	f, thick long-sleeves
Trousers:	a, naked	b, underwear	c, thin short panties or skirt
	d, thin trousers or long skirt	c, thick short panties or skirt	d, thick trousers or long skirt
Shoes:	a, barefoot	b, thin	c, middle	d, heavy

BEHAVIORAL ADAPTATION TO THERMAL ENVIRONMENTS

Please tick the frequency of adopting following behaviors responding to hot environments in your daily life (1 represents the lowest frequency and 5 represents the highest frequency).

	1	2	3	4	5
23. Opening doors for natural ventilation (NV);	○	○	○	○	○
24. Opening windows for NV;	○	○	○	○	○
25. Reducing clothes;	○	○	○	○	○
26. Reducing insulation, such as bamboo mat and sheets (clothes excluded);	○	○	○	○	○
27. Cold or frozen food and drink;	○	○	○	○	○
28. Mechanical fan;	○	○	○	○	○
29. Air-condition for cooling;	○	○	○	○	○
30. Swimming or shower;	○	○	○	○	○
31. Keeping calm;	○	○	○	○	○
32. Reduce usage of hotter space;	○	○	○	○	○
33. Adjusting thermostat;	○	○	○	○	○
34. Curtain or shutter	○	○	○	○	○
35. Reducing activities;	○	○	○	○	○
36. Vegetation cooling;	○	○	○	○	○
37. Evaporation effect;	○	○	○	○	○
38. Walking out in the evening;	○	○	○	○	○
39. Sleeping outdoors in the night;	○	○	○	○	○
40. Lower thermal comfort expectation (more tolerance).	○	○	○	○	○
	○	○	○	○	○

How do you think about the importance of the following properties driving your choice for cooling methods? (1 represents least important and 5 represents most important)

	1	2	3	4	5
41. Healthy;	○	○	○	○	○
42. Safety;	○	○	○	○	○
43. Convenience;	○	○	○	○	○
44. Thermal performance efficiency;	○	○	○	○	○
45. Economic efficiency.	○	○	○	○	○

OPEN QUESTIONTS

46. How old are you? ____
    a, less than 14 year old b, 15~44 years old c, 45~59 years old d, 60~75years old e, older than 75 years old

47. What is your gender? ____
    a, male b, female

48. What is the average income per person in your family? ____
    a, less than 800RMB b, 800~1500RMB c, 1500~3000RMB
    d, 3000~5000RMB e, 5000~10000RMB f, more than 10000RMB

49. How much money need you pay for the cooling per month on average in your family? ____
    a, 0~50RMB b, 50~100RMB c, 100~200RMB
    d, 200~300RMB e, 300~500RMB f, more than 500RMB

50. Do you adopt any other cooling methods which have not been mentioned in this questionnaire? If yes, please specify
    ____

51. If you are interested in our site measurements, please leave your contact method

____

Thanks for your participation!

Appendix E2: Questionnaire A for Investigation I (Summer & Chinese Version)

关于夏热冬冷地区居民热适应性的调查问卷（夏季）

这是一项由香港中文大学建筑学系及中国城市住宅研究中心支持的，关于夏热冬冷地区居民夏季热适应性的研究项目。该项目旨在了解该地区居民夏季在家中对热环境的适应情况，包括您所居住的住宅基本情况；您对热环境的反应——服装、行为活动及采用的各种降温方式等。您的意见将有助于我们深入了解该地区居民对热环境的适应能力和需求，故邀请您参加本次问卷调查。本问卷采用匿名形式填写，仅用于学术研究。您提供的信息我们都将予以严格保密，不会对您及您的家庭造成任何负面影响。

如需要帮助或有任何疑问，请联系该项目负责人熊燕。

电子邮件 xiongyan@cuhk.edu.hk 电话：852-29943014 传真：852-26036515

背景资料

1.您在武汉（与武汉相似气候区）居住了多少年_______？

A 1 年以下　B 1～3 年　C 4～6 年　D 8～12 年　E 12～20 年　F 20 年以上

2. 您家的建筑面积为________平方米？套内面积为_______平方米？

A 30 平方米以下　B30～60 平方米　C 61～90 平方米　D 91～120 平方米

E 121～200 平方米　F 200 平方米以上

3. 您家的格局是几室____？几厅____？几卫____？几厨____？几阳台____？

A 0　B1　C 2　D 3　E 4 及 4 以上

4. 您家属于什么类型的住宅？

A 低层住宅（1～3 层）　B 多层住宅（4～6 层）　C 中高层住宅（7～9 层）　D 高层住宅（十层及以上）

5. 您家有_______代人同住？常住人口为_______？

A 1 代　B 2 代　C 3 代　D 4 代或以上

A 1～2 位　B 3～4 位　C 5～6 位　D 7～8 位或以上

6. 您平均每天在家的时间约为　　？您家人平均每天在家的时间约为　　？

A 少于 6 小时　B 6～10 小时　C 10～14 小时　D14～18 小时　E 18～24 小时

7. 您家使用什么类型的空调？

A 无空调　B 独立式空调（窗机、挂机、柜机）　C 集中式空调　D 兼有 b、c 两种空调

8. 您家除空调外还有什么降温设备(可多选)?

A 无其它设备　B 电风扇　C 空调扇　D 其它

9. 您在使用空调降温时会采取哪种方式？开启空调的房间______开启空调的时间______。

A 单个房间开启　B 多个房间同时开启　C 所有房间开启

A 需要时候才开启，不需要时候关闭　B 保持一段时间开启　C 全天开启

对热环境的反应情况

10. 在夏季白天，您一般会将家里哪些门窗打开（可多选）_______？

A 全部开启　B 阳台门窗　C 厨卫门窗　D 卧室/书房门窗　E 客厅门窗　F 全部关闭

11. 白天一般当室内温度达到多少度时，您会使用空调降温______？

A 22 °C 以下　B22 °C 以上　C 25 °C 以上　D 28 °C 以上

E 32 °C 以上　F 35°C 以上　G 38°C 以上　H 42 °C 以上

12. 夜晚一般当室内温度达到多少度时，您会使用空调降温______？

A 22 °C 以下　B22 °C 以上　C 25 °C 以上　D 28 °C 以上

E 32 °C 以上　F 35°C 以上　G 38°C 以上　H 42 °C 以上

13. 夏季您较多在哪个时段开启空调降温（可多选）______？

A 从不开启　B 6:00～9:00　C 9:00～12:00　D 12:00～15:00　E 15:00～18:00

F 18:00～20:00　G 20:00～23:00　H 23:00～2:00　I 2:00～6:00

14. 您一般开启空调降温是为了更好的完成下列哪些家庭活动（可多选）______？

A 基本家庭活动，如必要的睡眠、洗浴、吃饭等　D 休闲活动，如看电视、听音乐、闲聊等

B 做家务，如清洁、烹饪等　E 社交活动，如接待朋友、打麻将、聚会等

C 照顾老人或孩子　F 工作或学习

15 您夏季在家的着装：上衣_____？下衣_____？鞋_____？

上衣：A 不着上衣　B 内衣　C 轻薄无袖或短袖上衣　D 轻薄长袖上衣
E 较厚短袖上衣　F 较厚长袖上衣
下衣：A 不着下衣　B 内裤　C 轻薄短裤或裙　D 轻薄长裤或裙
E 较厚短裤或裙　F 较厚长裤裙
鞋：A 赤脚　B 塑料拖鞋　C 棉布拖鞋　E 凉鞋　F 布鞋　G 皮鞋

各种消暑降温方式采用的频率：

(pcef1) 开门________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef2) 开窗________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef3) 减少着衣量________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef4) 使用凉席、竹坐垫等减少热阻的方式降温____? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef5) 食用冻饮冷食________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef6) 使用电风扇________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef7) 使用空调________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef8) 游泳、冲凉等________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef9) 心静自然凉________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef10) 减少西向房间或温度较高房间的使用频率____? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef11) 调节空调的设定温度________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef12) 使用窗帘百叶或其它遮阳方式________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef13) 减少活动量，如多休息，减少烹饪热加工等__? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef14) 利用绿化降温________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef15) 给门前、阳台或屋顶泼水降温________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef16) 傍晚去室外散步________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef17)夜间在室外睡觉________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁
(pcef18) 降低对热舒适的期待值________? A 从不 B 偶尔 C 经常 D 频繁 E 非常频繁

您觉得下列因素在您选择降温方式时的重要性如何？

18. 健康性________? A 不重要 B 不是特别重要 C 一般重要 D 比较重要 E 非常重要
19. 安全性________? A 不重要 B 不是特别重要 C 一般重要 D 比较重要 E 非常重要
20. 便捷性________? A 不重要 B 不是特别重要 C 一般重要 D 比较重要 E 非常重要
21. 增温效果性________? A 不重要 B 不是特别重要 C 一般重要 D 比较重要 E 非常重要
22. 经济性________? A 不重要 B 不是特别重要 C 一般重要 D 比较重要 E 非常重要
23. 您的年龄________?
A 14 岁及以下　B15～44 岁　C 45～64 岁　D 65～79 岁　E 80 岁及 80 岁以上
24. 您的性别________?
A 男性　B 女性
25. 您家人均月收入约在每月______元?
A 800 以下　B 800～1500　C 1500～3000　D 3000～5000　E 5000～10000　F10000 以上
26. 您家冬季高峰期用于室内降温的费用约为每月______元?
A 0～50　B 50～100　C 100～200　D 200～300　E 300～500　F 500 以上
27. 您还有哪些以上未提到的降温方式？请具体说明。

________________________________.

28. 如您对居民热适应性研究有兴趣，愿参与我们的实地测量，请与我们联系或留下您的联系方式。

________________________________.

答卷完毕，非常感谢您的合作！

Appendix E3: Questionnaire A for Investigation I (Winter & English Version)

Survey of Residents' Thermal Adaptation in the Hot-Sumer and Cold-Winter Region of China (winter)

This is a research project commissioned under the Center for Housing Innovations of the Chinese University of Hong Kong, which aims to identify the thermal adaptation of local residents in the Hot-summer and Cold-winter climatic zone of China. In order to have broad and objective findings, we sincerely invite you to this research and your answers will contribute to thermal comfort study and thermal environmental estimation in this climatic region.

The collected information will be treated **confidentially** and only used for research work. For enquiries and information, please contact Ms. XIONG Yan. Email: xiongyan@cuhk.edu.hk Tel: 852-9257665 Fax: 852-26036515

BACKGROUND INFORMATION

3. How many years have you lived in the climatic region of Hot-summer and Cold-winter in China, such as cities of Wuhan, Shanghai, Chongqing, Nanjing, Hangzhou, Changsha, etc.?______
   a, less than 1 year b, 1~3 years c, 4~6 years d, 8~12 years e, 12~20 years f, more than 20 years

4. What is the "gross floor area" of your house/apartment? _____ And how about the following room number? (please tick the circle corresponding to right number)
   a, less than 30 sqm b, 30~60 sqm c, 61~90 sqm d, 91~120 sqm e, 121~200 sqm f, more than 200 sqm

	0	1	2	3	4 or more
3. Bedroom + reading room number	○	○	○	○	○
4. Living room + dining room number	○	○	○	○	○
5. Bathroom number	○	○	○	○	○
6. Kitchen number	○	○	○	○	○
7. Balcony number	○	○	○	○	○

23. What kind of building type is your house/apartment? ____
    a, low-storey dwelling (1~3 storey)
    b, multi-storey dwelling (4~6 storey)
    c, Middle and high-storey dwelling (7~9 storey)
    d, High-storey dwelling (10 and more than 10 storey)

24. How many generations are living together in your house/apartment? ____
    a, 1 b, 2 c, 3 d, 4 and more than 4

25. How many people are living in your house/apartment permanently now? ____
    a, 1~2 b,3~4 c, 5~6 d, 7 and more than 7

26. How many hours do you stay in home per day on average? ____
    a, less than 6 hours b, 6~10 hours c, 10~14 hours d, 14~18 hours e, 18~24 hours

27. How many hours do your families stay in home per day on average? (if no families, please ignore this question) ____
    a, less than 6 hours b, 6~10 hours c, 10~14 hours d, 14~18 hours e, 18~24 hours

28. What type of air-condition do you use in your house/apartment? ____
    a, no air-condition b, individual control air-condition c, central control air-condition d, hybrid of b&c

29. What kind of additional heating equipment do you use in your house/apartment except of air-condition? ____
a, no other equipment   b, water heater   c, electrical heater   d, coal stove   e, gas heater   f, others

30. Generally, how do you control your heaters in terms of space? ____
a, switch on them just in one room
b, switch on them in several rooms
c, switch on them in all the rooms

31. Generally, how do you control your heaters in terms of time? ____
a, switch on them when you need and switch off them when you do not need
b, switch on them when you need and keep them on for a while even you do not need them really
c, switch on them all day

RESPONSE TO COLD ENVIRONMENTS

32. In the daytime of winter, what kind of windows & doors do you like to keep open? (multiple-choice question)____
a, none
b, windows & doors of balcony
c, windows & doors of kitchen and bathroom
d, windows & doors of bedroom and reading room
e, windows & doors of living room and dinning room
f, others

33. When the temperature decreases to ____°C, you will switch on air-conditioner for heating.
a, 18 °C   b, 12 °C   c, 6 °C   d, 0 °C   e, never switch on air-condition for heating

34. When the temperature decreases to ____°C, you will switch on heating equipments excluding air-conditioner heating.
a, 18 °C   b, 12 °C   c, 6 °C   d, 0 °C   e, never switch on air-condition for heating

35. Which following periods of time do you like to switch on heaters during? (multiple-choice question) ___

a, never	b, 6:00~9:00	c, 9:00~12:00	d, 12:00~15:00	e, 15:00~18:00
f, 18:00~20:00	g, 20:00~23:00	h, 23:00~2:00	i, 2:00~6:00	

36. Why kind of daily activities' quality do you want to maintain mostly through switching on heats? (multiple-choice question) ____
a, basic residential behavior, such as sleeping, eating, excretion, etc.
b, household work, such as cleaning, cooking, laundry, etc
c, taking care of children, elders or disable families
d, leisure, such as watching TV, listening music, chatting, etc.
e, social activities, such as entertaining friends, family gathering, meeting, etc.
f, working or studying

37. What is your dressing habit in home in winter? ____
a, light dressing, such as underwear+ shirt + trousers + shoes
b, moderate dressing, such as underwear+ shirt + sweater + 2 trousers + shoes
c, heavy dressing, such as underwear+ shirt + sweater + heavy jacket + heavy trousers +boots
d, extreme heavy dressing

BEHAVIORAL ADAPTATION TO THERMAL ENVIRONMENTS

Please tick the frequency of adopting following behaviors responding to cold environments in your daily life (1 represents the lowest frequency and 5 represents the highest frequency).

	1	2	3	4	5
23. Closing door;	○	○	○	○	○
24. Closing window;	○	○	○	○	○
25. Increasing clothes;	○	○	○	○	○
26. Increasing chair's or bed's insulation;	○	○	○	○	○
27. Hot food and drink;	○	○	○	○	○
28. Switching on semi-portable heater, such as electrical heater, coal stove, etc.;	○	○	○	○	○
29. Switching on air-condition for heating;	○	○	○	○	○
30. Using portable heat source, such as hot-water bag, etc.;	○	○	○	○	○
31. Basking in the sunshine;	○	○	○	○	○
32. Increasing the usage of warmer rooms;	○	○	○	○	○
33. Switching on fixed heaters, such as heater under floor or central heating;	○	○	○	○	○
34. Improving the building insulation or tightness	○	○	○	○	○
35. Doing more exercise;	○	○	○	○	○
36. Reducing outdoors activities;	○	○	○	○	○
37. Waking up later and going to bed earlier;	○	○	○	○	○
38. Body posture change;	○	○	○	○	○
39. Hot bath or hot footbath	○	○	○	○	○
40. Lower thermal comfort expectation (more tolerance).	○	○	○	○	○

How do you think about the importance of the following properties driving your choice for heating methods? (1 represents least important and 5 represents most important)

	1	2	3	4	5
41. Healthy;	○	○	○	○	○
42. Safety;	○	○	○	○	○
43. Convenience;	○	○	○	○	○
44. Thermal performance efficiency;	○	○	○	○	○
45. Economic efficiency.	○	○	○	○	○

OPEN QUESTIONTS

46. How old are you? ____
    a, less than 14 year old   b, 15~44 years old   c, 45~59 years old   d, 60~75years old   e, older than 75 years old

47. What is your gender? ____
    a, male   b, female

48. What is the average income per person in your family? ____
    a, less than 800RMB   b, 800~1500RMB   c, 1500~3000RMB
    d, 3000~5000RMB   e, 5000~10000RMB   f, more than 10000RMB

49. How much money need you pay for the heating per month on average in your family? ____
    a, 0~50RMB   b, 50~100RMB   c, 100~200RMB
    d, 200~300RMB   e, 300~500RMB   f, more than 500RMB

50. Do you adopt any other heating methods which have not been mentioned in this questionnaire? If yes, please specify ________________________________

51. If you are interested in our site measurements, please leave your contact method

    ____

Thanks for your participation!

Appendix E4: Questionnaire A for Investigation I (Winter & Chinese Version)

关于夏热冬冷地区居民热适应性的调查问卷（冬季）

这是一项由香港中文大学建筑学系及中国城市住宅研究中心支持的，关于夏热冬冷地区居民冬季热适应性的研究项目。该项目旨在了解该地区居民冬季在家中对热环境的适应情况，包括您所居住的住宅基本情况；您对热环境的反应——服装、行为活动及采用的各种取暖方式等。您的意见将有助于我们深入了解该地区居民对热环境的适应能力和需求，故邀请您参加本次问卷调查。 本问卷采用匿名形式填写，仅用于学术研究。您提供的信息我们都将予以严格保密，不会对您及您的家庭造成任何负面影响。

如需要帮助或有任何疑问，请联系该项目负责人熊燕。

电子邮件 xiongyan@cuhk.edu.hk 电话：852-29943014 传真：852-26036515

背景资料

1.您在武汉（与武汉相似气候区）居住了多少年________？

A 1 年以下 B 1～3 年 C 4～6 年 D 8～12 年 E 12～20 年 F 20 年以上

2. 您家的建筑面积为________平方米？套内面积为________平方米？

A 30 平方米以下 B30～60 平方米 C 61～90 平方米 D 91～120 平方米 E 121～200 平方米 F 200 平方米以上

3. 您家的格局是几室_____？几厅_____？几卫_____？几厨_____？几阳台_____？

A 0 B1 C 2 D 3 E 4 及 4 以上

4. 您家属于什么类型的住宅？

A 低层住宅（1～3 层） B 多层住宅（4～6 层） C 中高层住宅（7～9 层） D 高层住宅（十层及以上）

5. 您家有________代人同住？常住人口为________？

A 1 代 B 2 代 C 3 代 D 4 代或以上

A 1～2 位 B 3～4 位 C 5～6 位 D 7～8 位或以上

6. 您平均每天在家的时间约为________？您家人平均每天在家的时间约为________？

A 少于 6 小时 B 6～10 小时 C 10～14 小时 D14～18 小时 E 18～24 小时

7. 您家使用什么类型的空调？

A 无空调 B 独立式空调（窗机、挂机、柜机） C 集中式空调 D 兼有 b、c 两种空调

8. 您家除空调外还有什么取暖设备？(可多选)

A 无其它设备 B 暖气 C 电取暖器（油烃、暖风机、电炉等） D 煤炉 E 燃气炉 F 其它

9. 您使用取暖设备会采取哪种方式？开启空调的房间________开启空调的时间________。

A 单个房间开启 B 多个房间同时开启 C 所有房间开启

A 需要时候才开启，不需要时候关闭 B 保持一段时间开启 C 全天开启

对冷环境的反应情况

10. 在冬季白天，您一般会将家里哪些门窗打开________？(可多选)

A 全部关闭 B 阳台门窗 C 厨卫门窗 D 卧室/书房门窗 E 客厅门窗

11. 一般当室内温度达到多少度时，您会使用空调取暖________？

A 18 °C 以下 B12 °C 以下 C 6 °C 以下 D 0 °C 以下 E 从不开启

12. 一般当室内温度达到多少度时，您会开启除空调外的取暖设备________？

A 18 °C 以下 B12 °C 以下 C 6 °C 以下 D 0 °C 以下 E 从不开启

13. 冬季您较多在哪个时段开启取暖设备（可多选）_______？

A 从不开启 B 6:00～9:00 C 9:00～12:00 D 12:00～15:00 E 15:00～18:00 F 18:00～20:00 G 20:00～23:00 H 23:00～2:00 I 2:00～6:00

14. 您一般开启取暖设备是为了更好的完成下列哪些家庭活动_______？

A 基本家庭活动，如必要的睡眠、洗浴、吃饭等 D 休闲活动，如看电视、听音乐、闲聊等

B 做家务，如清洁、烹饪等 E 社交活动，如接待朋友、打麻将、聚会等

C 照顾老人或孩子　　　　F 工作或学习

15.冬季您在家的着装一般为______？

A 轻薄着装　B 中等着装　C 厚着装　D 极厚着装（包括帽子、手套、围巾、靴子等）

各种采暖增温方式采用的频率：

(pcef1) 关门______________________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef2) 关窗______________________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef3) 增加着衣量__________________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef4) 增加厚坐垫、被褥等____________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef5) 食用热饮、热食________________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef6) 取暖器（电热器、电热毯、油炡等）______？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef7) 使用空调____________________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef8) 便携式取暖器（电饼、热水袋、暖包等）_？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef9) 外出（阳台上）晒太阳____________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef10) 增加较暖房间（有日照）的使用频率____？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef11) 地暖（水暖/电暖）/暖气__________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef12) 提高房屋密封性和保温性能______________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef13) 增加活动量（做运动）__________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef14) 减少外出时间和次数____________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef15) 提前入睡或较晚起床____________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef16) 蜷缩姿势____________________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

(pcef17) 降低对热舒适的期待值__________________？A 从不　B 偶尔　C 经常　D 频繁 E 非常频繁

您觉得下列因素在您选择采暖方式时的重要性如何？

18. 健康性____________________？A 不重要　B 不是特别重要　C 一般重要　D 比较重要　E 非常重要

19. 安全性____________________？A 不重要　B 不是特别重要　C 一般重要　D 比较重要　E 非常重要

20. 便捷性____________________？A 不重要　B 不是特别重要　C 一般重要　D 比较重要　E 非常重要

21. 增温效果性________________？A 不重要　B 不是特别重要　C 一般重要　D 比较重要　E 非常重要

22. 经济性____________________？A 不重要　B 不是特别重要　C 一般重要　D 比较重要　E 非常重要

23. 您的年龄________？

A 14 岁及以下　B15～44 岁　C 45～64 岁　D 65～79 岁　E 80 岁及 80 岁以上

24. 您的性别____________？

A 男性　B 女性

25. 您家人均月收入约在每月______元？

A 800 以下　B 800～1500　C 1500～3000　D 3000～5000　E 5000～10000　F10000 以上

26. 您家冬季高峰期用于室内取暖的费用约为每月______元？

A 0～50　B 50～100　C 100～200　D 200～300　E 300～500　F 500 以上

27. 您还有哪些以上未提到的采暖方式？请具体说明。

____.

28. 如您对居民热适应性研究有兴趣，愿参与我们的实地测量，请与我们联系或留下您的联系方式。

____.

答卷完毕，非常感谢您的合作！

Appendix E5: Questionnaire B for Investigation II (Summer& English Version)

Recording Form for Thermal Adaptation in Wuhan (summer)
Part1：Building Information

Investigator:_________________.

BACKGROUND INFORMATION

Contact：

_；

Family member: ______person，_______generation， investigated person_________________；

(year & day)Recording data: ___________year _______________month day；

(time) Recording time: from ______________to______________， interval minute。

Others：

(b l code) BUILDING DESCRIPTION

Gross floor area: （ ） sqm； Usable floor area （ ） sqm；

Operable window area： （ ） sqm；Orientation: （ ）； Ceiling height： （ ） m；

Description of building surroundings：

PLAN

Recording Form for Thermal Adaptation in Wuhan (summer)
Part2：Occupant Information

INTRODUCTION: The following measuring scale means the subjective sensation corresponding to thermal environment. If you feel extreme hot, you can mark the line on the right of "Hot" point as second vertical bar; if your feeling is just right, you can mark the line at "Neutral" point as the first vertical bar. The other measuring scales are similar.

Cold — Cool — Slightly Cool — Neutral — Slightly Warm — Warm — Hot

OCCUPANT'S RESPONSE TO THERMAL ENVIRONMENTS

1. Have you been in the air-conditioned room including indoor space or bus, car, taxi, etc.?
( ) Yes ( ) No

2. How do you feel the current thermal environment? ________

Cold — Cool — Slightly Cool — Neutral — Slightly Warm — Warm — Hot

3. You want to change the current thermal environment? ________

warmer — no change — cooler

4. How do you feel current humidity? ________

Too damp — a little damp — just right — a little dry — too dry

5. How do you feel the current wind velocity? ________

Too still — a little still — just right — a little windy — too windy

6. Your general thermal comfort? ________

comfortable — slightly warm uncomfortable — hot uncomfortable — extremely hot uncomfortable

7. (tsa)Can you accept the current thermal environment only based your individual concerns? ________

acceptable — slightly unacceptable — unacceptable — extremely unacceptable

ACTIVITY

(act10) Activity happing now____________________________; (act20) Activity happened 20m before________________;
(act30) Activity happened 30m before____________________; (act60) Activity happened 1h before__________________;

CLOTHES AND CHAIR INSULATION

Please describe your clothing wearing in details____;
If you are sitting, please indicate the chair texture:
( ) cambric ( ) leather ( ) wood ( ) metal ( ) plastics ( ) stone.

(Sub)___(sex)__(age)____(heal)health condition____(car)career_____, Recod N._____,
Recording data:____year___month___day; Recording time: from___to___, interval______minute.

Recording Form for Thermal Adaptation in Wuhan (summer)
Part3：Indoor/outdoor climate information

For investigator：

(blcode)building number _________ (Sub) investigator_______________.
(stiav)average hour of staying in home________________ (h) , serials number________________,

Metabolic rate and Insulation

(met)：（　　）；　(clo)：（　　）；　(upholst) ：（　　）；　(insul) ：（　　）；

Indoor Thermal Environment Observation

(ta)：（　）°C；
(vel) ：（　）m/s;
(tg) ：（　）°C;
（rh）：（　）；

Calculated Thermal Comfort Indices

(top) ：（　）°C;
(et) ：（　）°C；
(set) ：（　）°C ；
(pmv) ：（　）；
(pdd) ：（　）；

Outdoor Thermal Environment Observation

(ota_m) ：（　）°C;
(ovel_m) ：（　）m/s;
（orh）：（　）

Outdoor Meteorological Observation

(day15_ta)：（　）°C
(day06_ta)：（　）°C
(dayav_ta)：（　）°C
(day15_rh)：（　）
(day06_rh)：（　）
(dayav_rh)：（　）

Supplementary description of indoor thermal environments (operation of heater and occupants' activities):

Appendix E6: Questionnaire B for Investigation II (Summer& Chinese Version)

武汉市居民热适应性样本记录表（夏季）
第一部分：建筑信息

记录者________________.

样本基本资料

联系方式：

_:

家庭成员______人，共_____代人，被访者有_____人，在武汉分别居住时间__________；

记录日期 ________________年 _________________月日；

记录时间 ________________至_________________，每隔_________分钟记录一次。

其它：

房屋说明

建筑面积（　　）平方米；套内面积（　　）平方米；可开启门窗面积：（　　）平方米

朝向：（　　）　　层高：（　　）米

建筑周边环境描述：

房屋平、立面图：

武汉市居民热适应性样本记录表（夏季）
第二部分：个人信息

使用指南：下图横线上的刻度表示您的对当前热环境的感受强弱和方向，如第一题中的第一个黑点位置表示“冷”，第四个黑点位置表示“不冷不热感觉刚刚好”，第七个黑点位置表示“热”。如果你此时的感受是刚好不冷不热，则应该将竖线画在“不冷不热”对应的黑点上，如范例中第一条竖线所示；如果您此时的感受是非常热，则您可以将竖线化在第七个黑点之后，如范例中第二条竖线。其它题目填写方式类似。

冷　凉　有点凉　不冷不热刚刚好　有点暖　暖　热

被访者热舒适度

1. 过去 15 分钟内您有没有在有空调或暖气的地方待过（包括室内或巴士、出租车等）？请勾选。
   （　）有过　（　）没有

2. 您此次此刻的热感觉如何？

冷　凉　有点凉　不冷不热刚刚好　有点暖　暖　热

3. 您现在希望

再热一点　不变化　再冷一点

4.您此时此刻感觉空气

很潮湿　有点潮湿　不干不湿　有点干燥　很干燥

5.您觉得此时的风速

太小　小了点　刚好　大了点　太大

6. 整体来说您此时的热舒适感受如何？

很舒服　有点不舒服　不舒服　极其不舒服

7.对于目前所处的热环境，如果仅考虑您个人的感受，您能接受吗?

完全能接受　有点不能接受　难以接受　完全不能接受

被访者新陈代谢速度

您当前活动________；10-20 分钟前活动________；20-30 分钟前活动________；30-60 分钟前活动________；

被访者着装及热阻

请详细描述您此时的着装（包括内衣外）

________________________________；

如果您处于坐姿，请说明坐具的材质（勾选）：
（ ）布、（ ）皮、（ ）木头、（ ）金属、（ ）塑料；（ ）石头。

记录者______性别______年龄______健康状况______职业______记录序号______；记录日期_____年_____月_____日，记录时间_____时_____分秒，记录间隔_____分。

武汉市居民热适应性样本记录表（夏季）
第三部分：气候信息

工作人员记录项：

(blcode)建筑物号码 ____________________ （Sub）记录者_____________.
(stiav)平均在家时间______________ （小时），记录序号______________,

新陈代谢速度及热阻

(met)平均代谢速度（　　）met；　(clo)服装热阻：（　　）clo；
(upholst)椅子热阻（　　）clo；　(insul)衣服＋椅子的热阻（　　）clo

室内物理参数

(ta)空气温度（　）°C；
(vel)风速（　）m/s；
(tg)黑球温度（　）°C；
（rh）相对湿度（　）%；

计算参数

(top)操作温度（　）°C；
(et) 有效温度（　）°C；
(set)标准有效温度（　）°C；
(pmv) 预测平均投票（　）；
(pdd) 预测不满意百分比（　）；

住宅外物理参数（测量数据）

(ota)空气温度（　）°C；
(ovel)风速（　）m/s；
(otg)黑球温度（　）°C；
（orh）相对湿度（　）%；

当地气象参数（气象站数据）

(day15_ta) 室外 15：00（最高）空气温度：（　　）° C
(day06_ta) 室外 6：00（最低）空气温度：（　　）° C
(dayav_ta) 室外当天平均温度：（　　）° C
(day15_rh) 室外 15：00（最小）相对湿度：（　　）
(day06_rh) 室外 6：00（最大）相对湿度：（　　）
(dayav_rh) 室外当天平均相对湿度：（　　）

家中热环境补充描述（包括使用降温设备的情况及样本的行为）

Appendix E7: Questionnaire B for Investigation II (Winter & English Version)

Recording Form for Thermal Adaptation in Wuhan (winter)
Part1：Building Information

Investigator:________________.

BACKGROUND INFORMATION

Contact：

_；

Family member: ______person， ______generation， investigated person______________；

(year & day)Recording data: ___________year ______________month day；

(time) Recording time: from _____________to_____________， interval minute。

Others：

(b l code) BUILDING DESCRIPTION

Gross floor area:（ ）sqm； Usable floor area（ ）sqm；

Operable window area：（ ）sqm；Orientation:（ ）； Ceiling height：（ ）m；

Description of building surroundings：

PLAN

Recording form for thermal adaptation in Wuhan (winter)
Part2: Occupant information

INTRODUCTION: The following measuring scale means the subjective sensation corresponding to thermal environment. If you feel extreme cold, you can mark the line on the left of "Cold" point as second vertical bar; if your feeling is just right, you can mark the line at "Neutral" point as the first vertical bar. The other measuring scales are similar.

Cold — Cool — Slightly Cool — Neutral — Slightly Warm — Warm — Hot

OCCUPANT'S RESPONSE TO THERMAL ENVIRONMENTS

1. Have you been in the air-conditioned room including indoor space or bus, car, taxi, etc.?
   ( ) Yes ( ) No

2. How do you feel the current thermal environment? ________

Cold — Cool — Slightly Cool — Neutral — Slightly Warm — Warm — Hot

3. You want to change the current thermal environment? ________

warmer — no change — cooler

4. How do you feel current humidity? ________

Too damp — a little damp — just right — a little dry — too dry

5. How do you feel the current wind velocity? ________

Too still — a little still — just right — a little windy — too windy

6. Your general thermal comfort? ________

comfortable — slightly cool uncomfortable — cool uncomfortable — extremely cold uncomfortable

7. (tsa)Can you accept the current thermal environment only based your individual concerns? ________

acceptable — slightly unacceptable — unacceptable — extremely unacceptable

ACTIVITY

(act10) Activity happing now____________________________: (act20) Activity happened 20m before_________________;
(act30) Activity happened 30m before____________________: (act60) Activity happened 1h before_________________:

CLOTHES AND CHAIR INSULATION

Please describe your clothing wearing in details_______________________________________:
If you are sitting, please indicate the chair texture:
( ) cambric ( ) leather ( ) wood ( ) metal ( ) plastics ( ) stone.

(Sub)______(sex)____(age)_______(heal)health condition_______(car)career______, Recod N._____,
Recording data: ____year___month____day; Recording time: from___to____, interval minute.

Recording Form for Thermal Adaptation in Wuhan (winter)
Part3：Indoor/outdoor climate information

For investigator：

(blcode)building number _________ (Sub) investigator______________.
(stiav)average hour of staying in home_________________ (h) , serials number_______________,

Metabolic rate and Insulation

(met)： ( ) ; (clo)： ( ) ; (upholst) ： ( ) ; (insul) ： ( ) ;

Indoor Thermal Environment Observation

(ta)： ( ) °C ;
(vel) ： ( ) m/s;
(tg) ： ( ) °C;
(rh) ： ( ) ;

Calculated Thermal Comfort Indices

(top) ： ( ) °C;
(et) ： ( ) °C ;
(set) ： ( ) °C ;
(pmv) ： ( ) ;
(pdd) ： ( ) ;

Outdoor Thermal Environment Observation

(ota_m) ： ( ) °C;
(ovel_m) ： ( ) m/s;
(orh) ： ( )

Outdoor Meteorological Observation

(day15_ta)： ( ) °C
(day06_ta)： ( ) °C
(dayav_ta)： ( ) °C
(day15_rh)： ( )
(day06_rh)： ( )
(dayav_rh)： ( )

Supplementary description of indoor thermal environments (operation of heater and occupants' activities):

Appendix E8: Questionnaire B for Investigation II (Winter & Chinese Version)

武汉市居民热适应性样本记录表（冬季）
第一部分：建筑信息

记录者________________.

样本基本资料

联系方式：____;

家庭成员______人，共_____代人，被访者有_____人，在武汉分别居住时间__________;

记录日期 _____________年 _________________月 ____________________日；

记录时间 ___________________至________________，每隔__________分钟记录一次。

其它：

房屋说明

建筑面积（　　）平方米；套内面积（　　）平方米；可开启门窗面积：（　　）平方米

朝向：（　　）　　层高：（　　）米

建筑周边环境描述：

房屋平、立面图：

武汉市居民热适应性样本记录表（冬季）
第二部分：个人信息

使用指南：下图横线上的刻度表示您的对当前热环境的感受强弱和方向，如第一题中的第一个黑点位置表示“冷”，第四个黑点位置表示“不冷不热感觉刚刚好”，第七个黑点位置表示“热”。如果您此时的感受是非常冷，则您可以将竖线化在第一个黑点之前，如范例中第一条竖线；如果你此时的感受是刚好不冷不热，则应该将竖线画在“不冷不热”对应的黑点上，如范例中第二条竖线所示。其它题目填写方式类似。

冷　　凉　　有点凉　　不冷不热刚刚好　　有点暖　　暖　　热

被访者热舒适度

1. 过去 15 分钟内您有没有在有空调或暖气的地方待过（包括室内或巴士、出租车等）？请勾选。
（　）有过　（　）没有

2. 您此次此刻的热感觉如何？

冷　　凉　　有点凉　　不冷不热刚刚好　　有点暖　　暖　　热

3. 您现在希望

再热一点　　不变化　　再冷一点

4.您此时此刻感觉空气

很潮湿　　有点潮湿　　不干不湿　　有点干燥　　很干燥

5.您觉得此时的风速

太小　　小了点　　刚好　　大了点　　太大

6. 整体来说您此时的热舒适感受如何？

很舒服　　有点不舒服　　不舒服　　极其不舒服

7.对于目前所处的热环境，如果仅考虑您个人的感受，您能接受吗?

完全能接受　　有点不能接受　　难以接受　　完全不能接受

被访者新陈代谢速度

您当前活动__________；10-20 分钟前活动__________；20-30 分钟前活动__________；30-60 分钟前活动__________；

被访者着装及热阻

请详细描述您此时的着装（包括内衣外）

____；

如果您处于坐姿，请说明坐具的材质（勾选）：
（ ）布、（ ）皮、（ ）木头、（ ）金属、（ ）塑料；（ ）石头。

记录者__________性别________年龄___________健康状况______________职业__________记录序号__________；

记录日期______年______月________日，记录时间____时_____分_____秒，记录间隔______分。

武汉市居民热适应性样本记录表（冬季）
第三部分：气候信息

工作人员记录项：

(blcode)建筑物号码 ____________________ (Sub) 记录者______________.
(stiav)平均在家时间______________ （小时），记录序号______________，

新陈代谢速度及热阻

(met)平均代谢速度（　　　）met；　　(clo)服装热阻：（　　　）clo；
(upholst)椅子热阻（　　　）clo；　　(insul)衣服＋椅子的热阻（　　　）clo

室内物理参数

(ta)空气温度（　　）°C；
(vel)风速（　　）m/s；
(tg)黑球温度（　　）°C；
(rh) 相对湿度（　　）%；

计算参数

(top)操作温度（　　　）°C；
(et) 有效温度（　　　）°C；
(set)标准有效温度（　　　）°C；
(pmv) 预测平均投票（　　　）；
(pdd) 预测不满意百分比（　　　）；

住宅外物理参数（测量数据）

(ota)空气温度（　　）°C；
(ovel)风速（　　）m/s；
(otg)黑球温度（　　）°C；
(orh) 相对湿度（　　）%；

当地气象参数（气象站数据）

(day15_ta) 室外 15：00（最高）空气温度：（　　　　　）° C
(day06_ta) 室外 6：00（最低）空气温度：（　　　　　）° C
(dayav_ta) 室外当天平均温度：（　　　　　）° C
(day15_rh) 室外 15：00（最小）相对湿度：（　　　　　）
(day06_rh) 室外 6：00（最大）相对湿度：（　　　　　）
(dayav_rh) 室外当天平均相对湿度：（　　　　　）

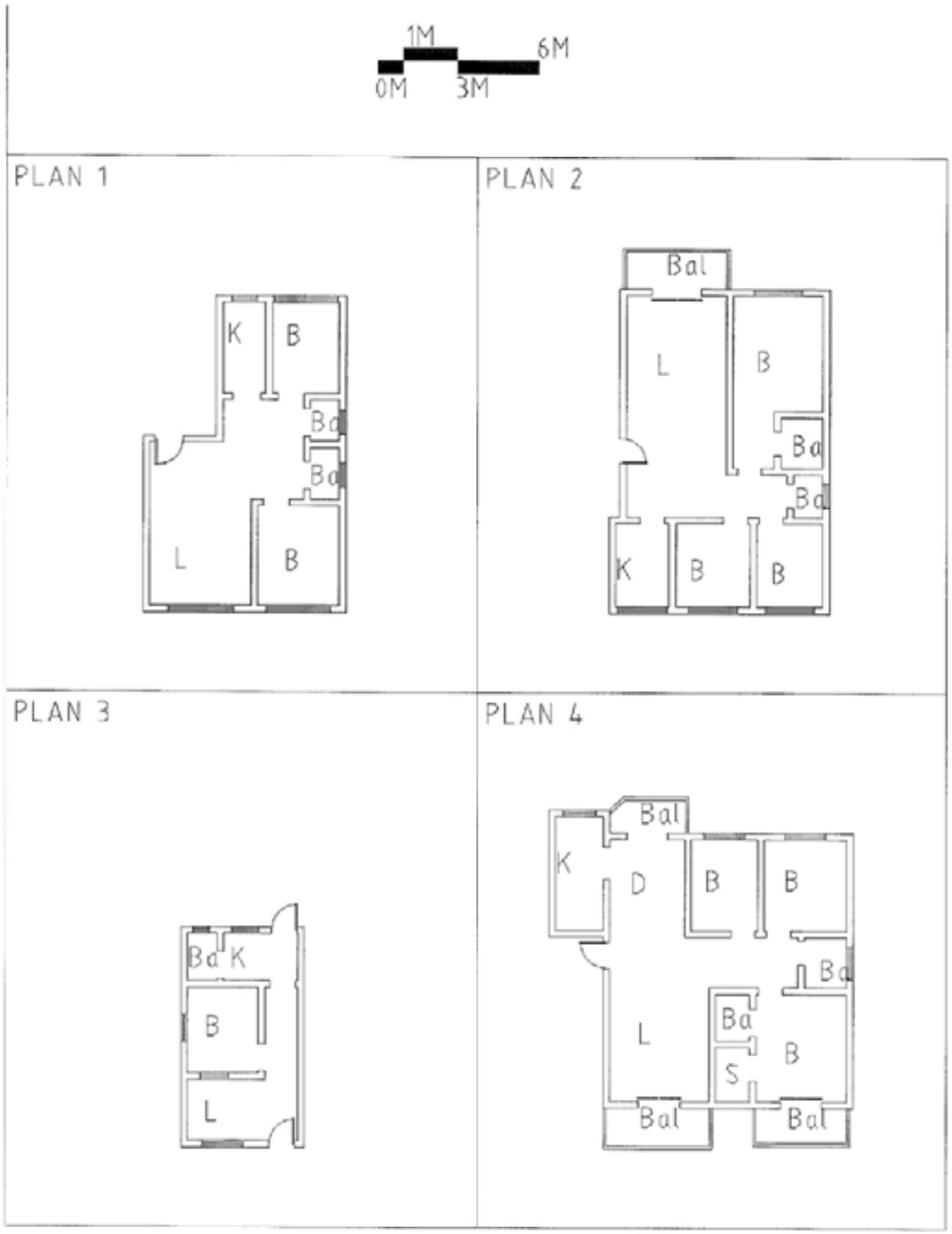
家中热环境补充描述(包括使用取暖设备的情况及样本的行为)

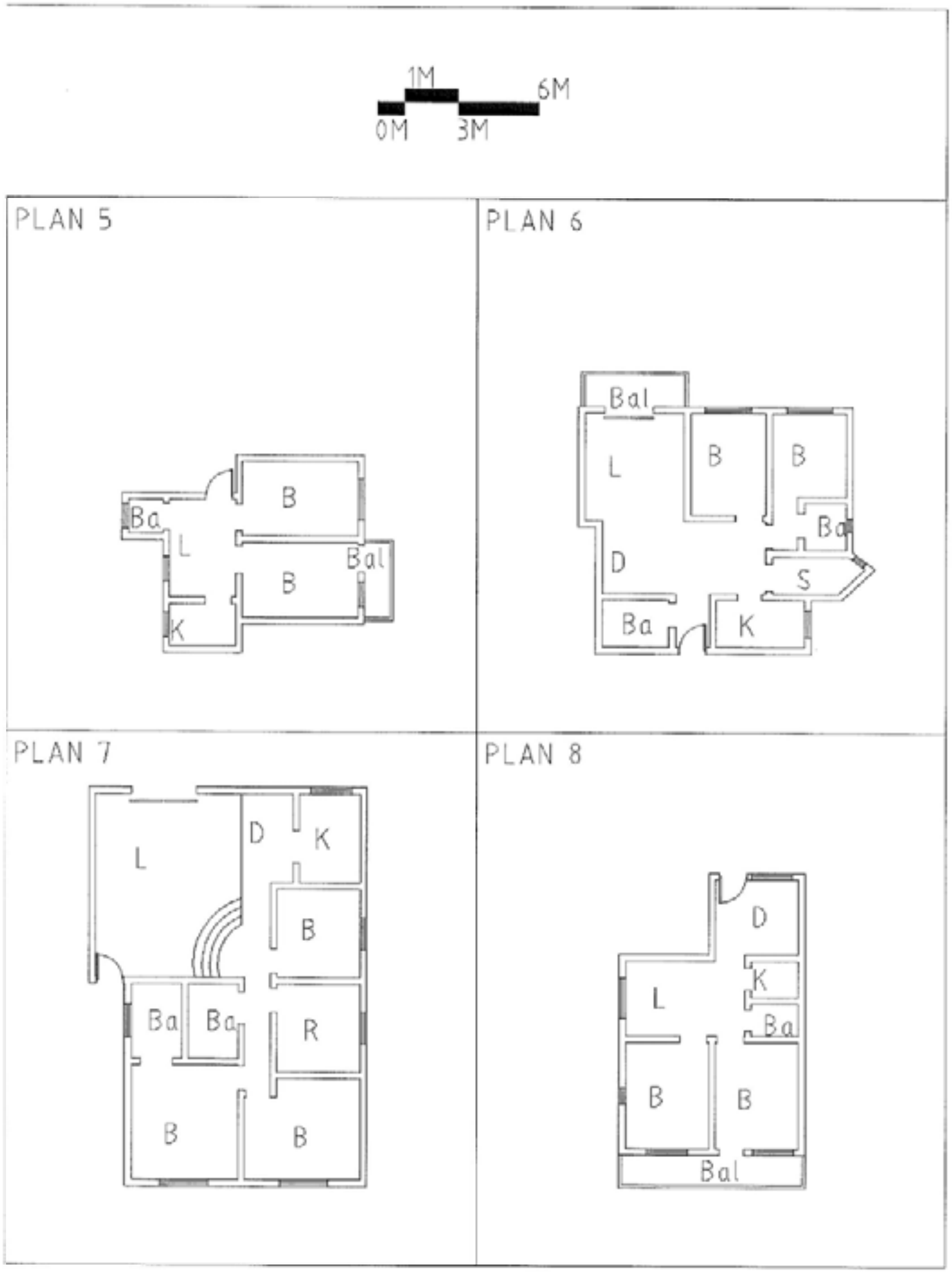
Appendix F: Investigated Apartments Plan

Abbreviation:

L: Living room; B: Bedroom; Ba: Bathroom;

K: Kitchen; Bal: Balcony: R: Reading room

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Bal
B
K
PLAN 6
Bal
L
B
B
Ba
D
S
Ba
K
PLAN 7
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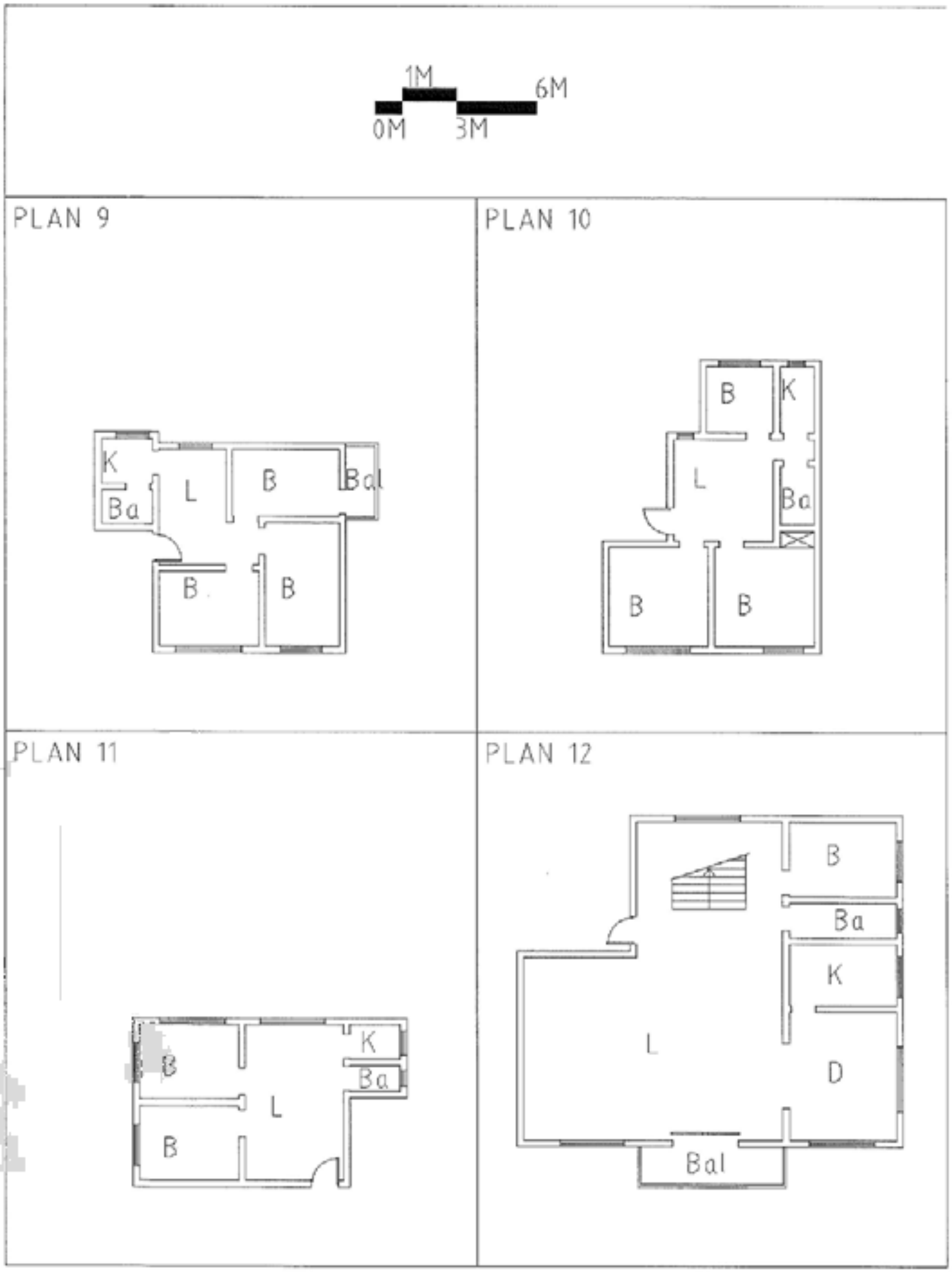
K
L
B
Ba
Ba
R
B
B
PLAN 8
D
K
L
Ba
B
B
Bal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PLAN 12
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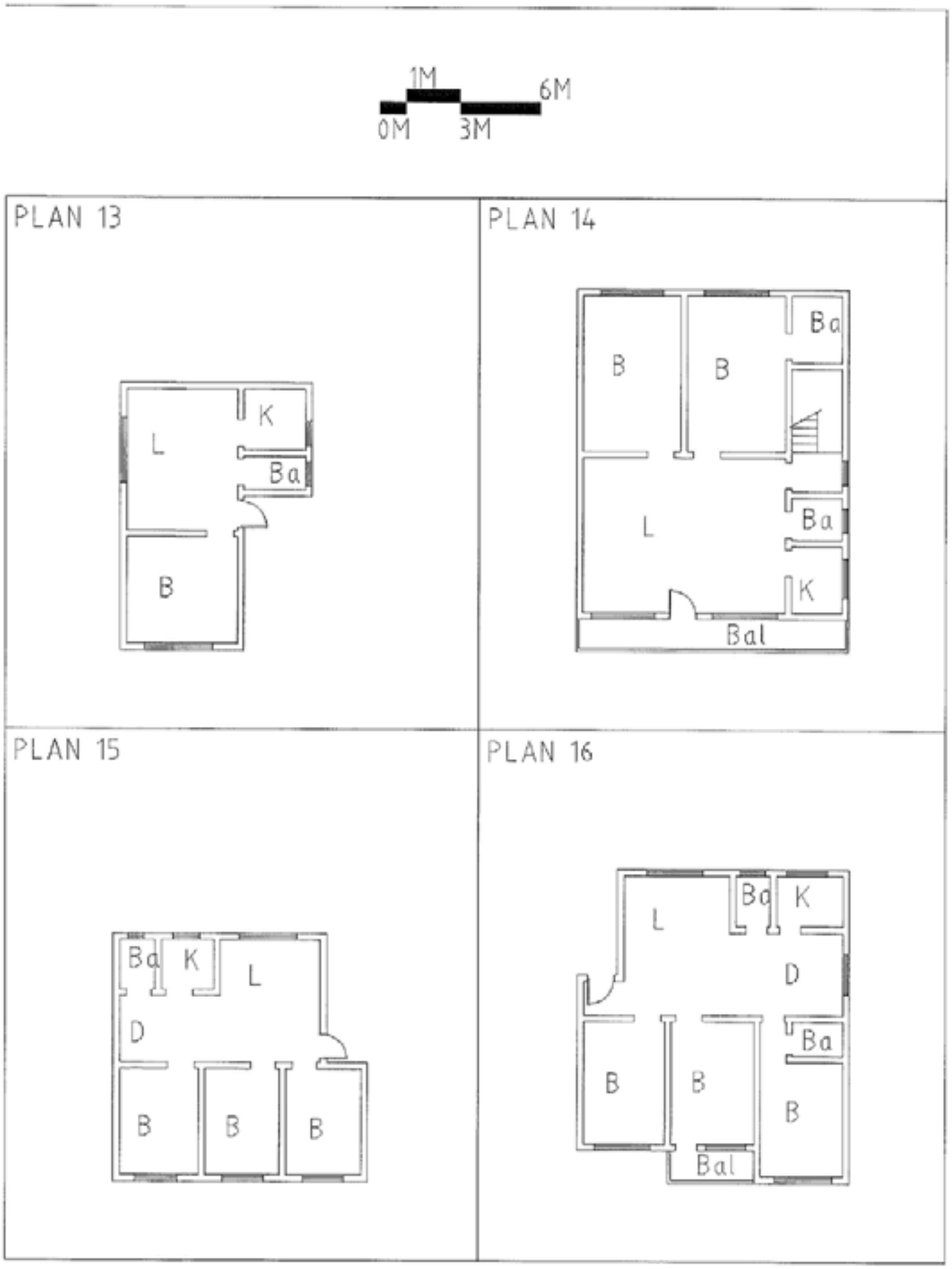
Ba
K
L
D
Bal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B
PLAN 14
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B
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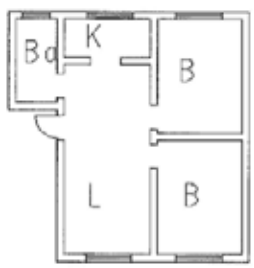
L
Ba
K
Bal
PLAN 15
Ba
K
L
D
B
B
B
PLAN 16
Ba
K
L
D
Ba
B
B
B
Bal

PLAN 17



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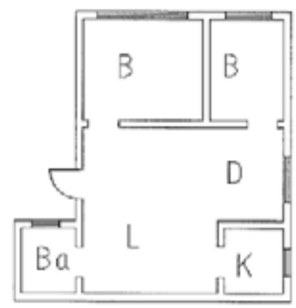
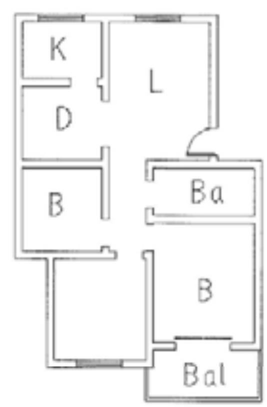
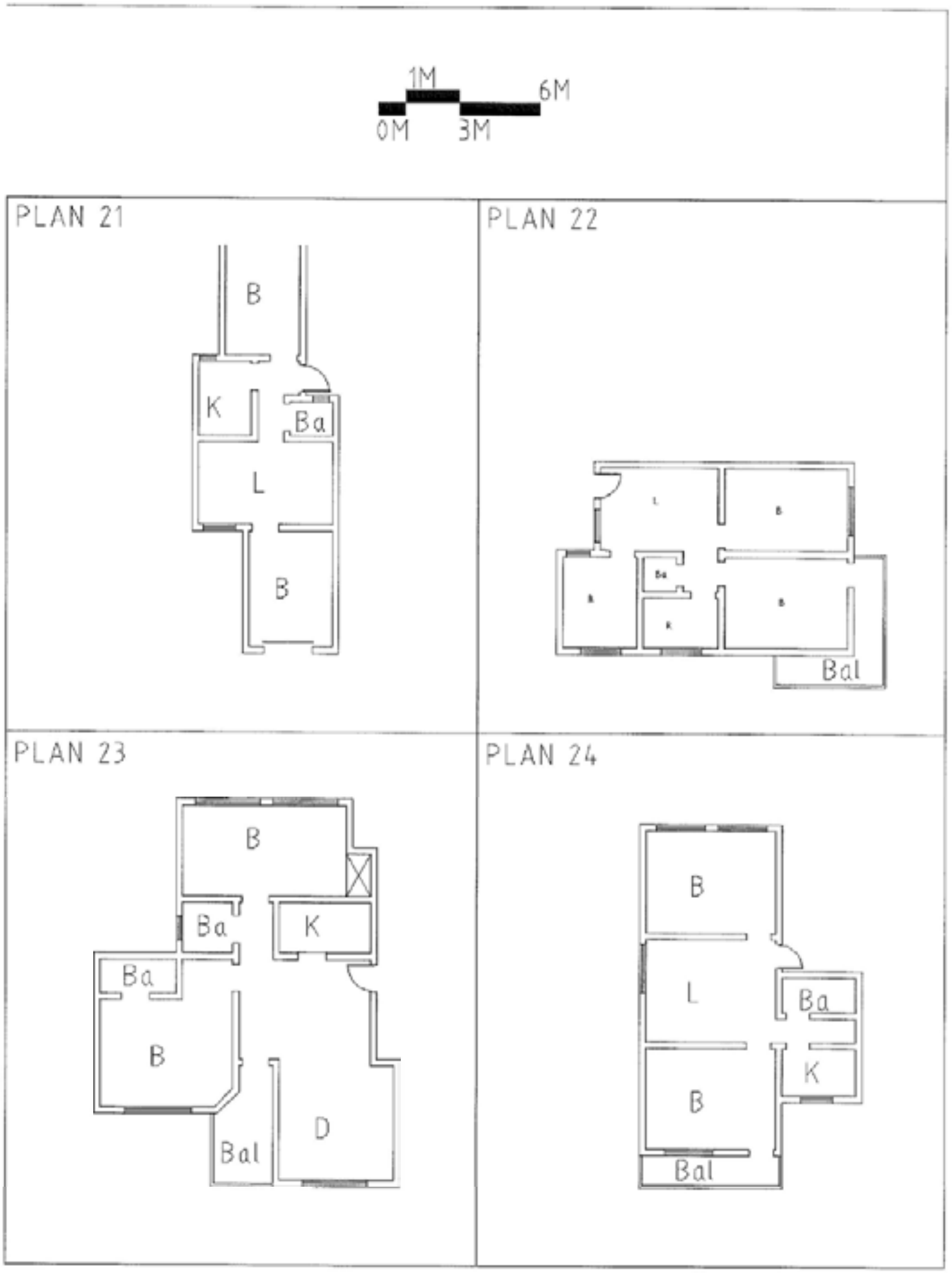


PLAN 19

PLAN 20

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K
Ba
L
B
PLAN 22
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PLAN 23
B
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K
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B
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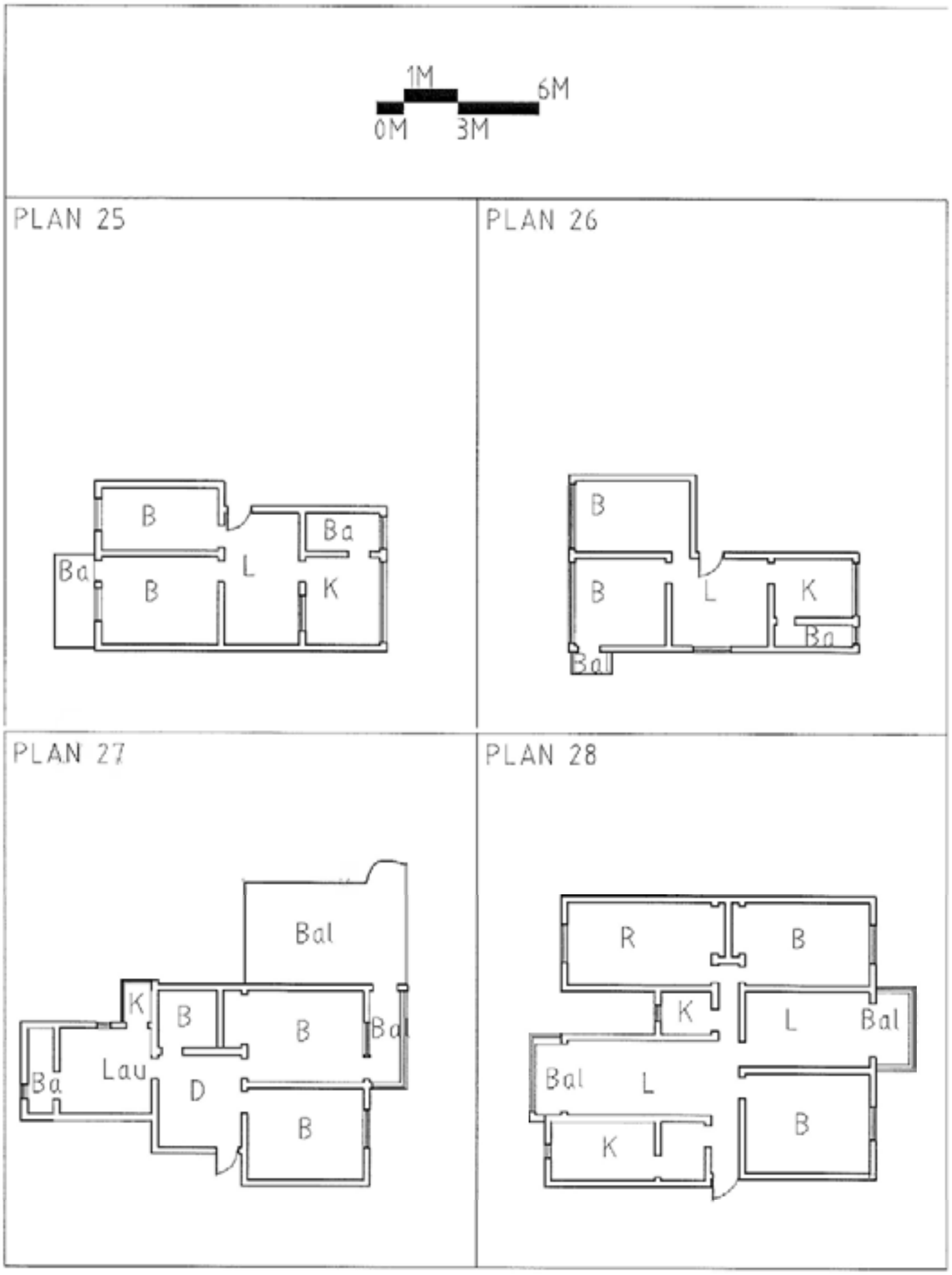
D
PLAN 24
B
L
Ba
K
B
Bal



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PLAN 25
B
Ba
Ba
L
B
K
PLAN 26
B
B
L
K
Ba
Bal
PLAN 27
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K
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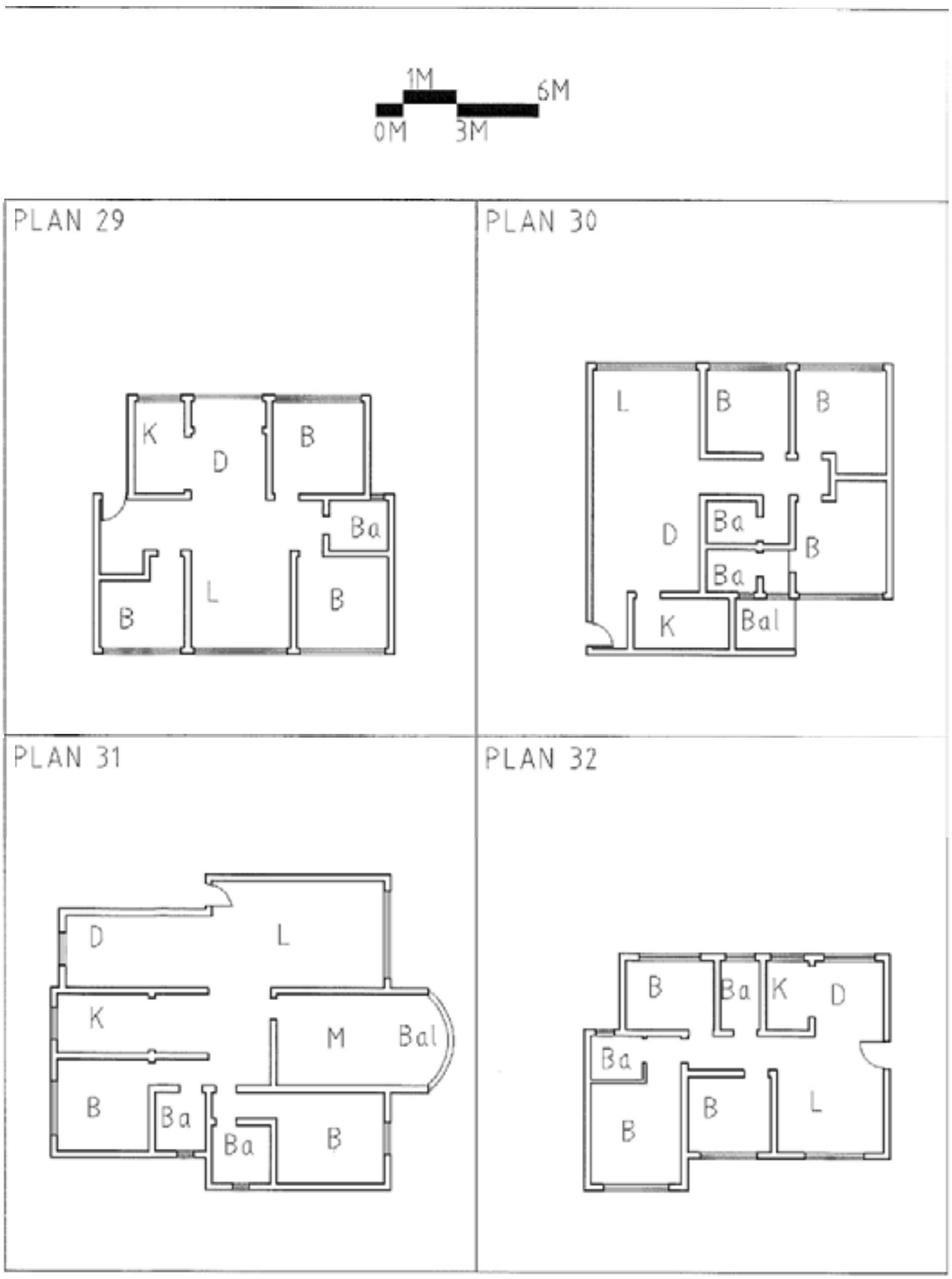
B
Bal
Lau
Ba
D
B
PLAN 28
R
B
K
L
Bal
Bal
L
B
K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PLAN 29
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Ba
L
B
B
PLAN 30
L
B
B
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D
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Ba
K
Bal
PLAN 31
D
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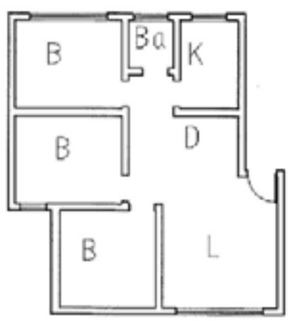
K
M
Bal
B
Ba
Ba
B
PLAN 32
B
Ba
K
D
Ba
B
L
B

PLAN 33



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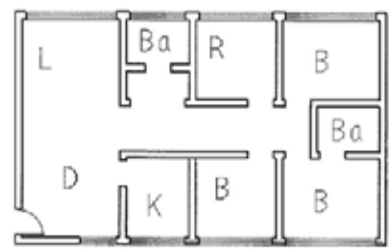

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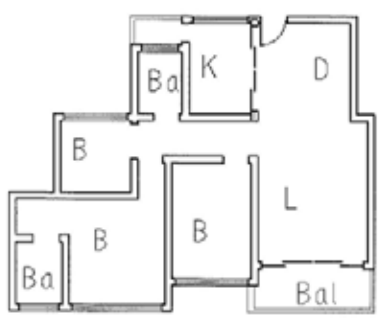

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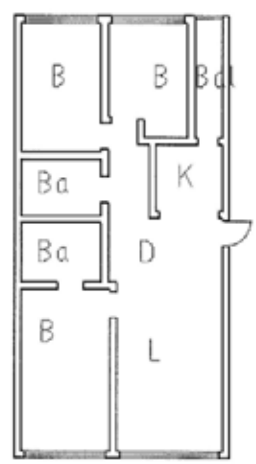

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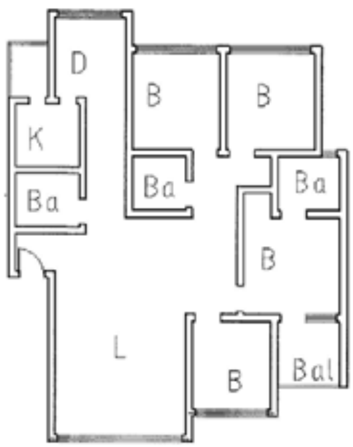

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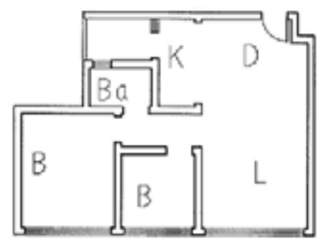

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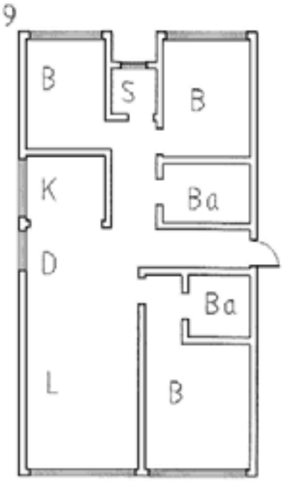

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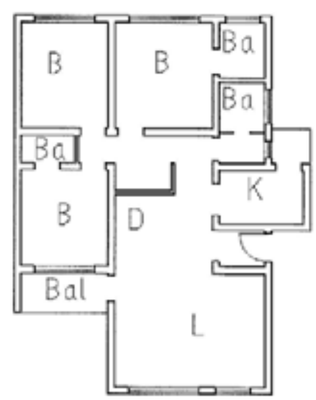

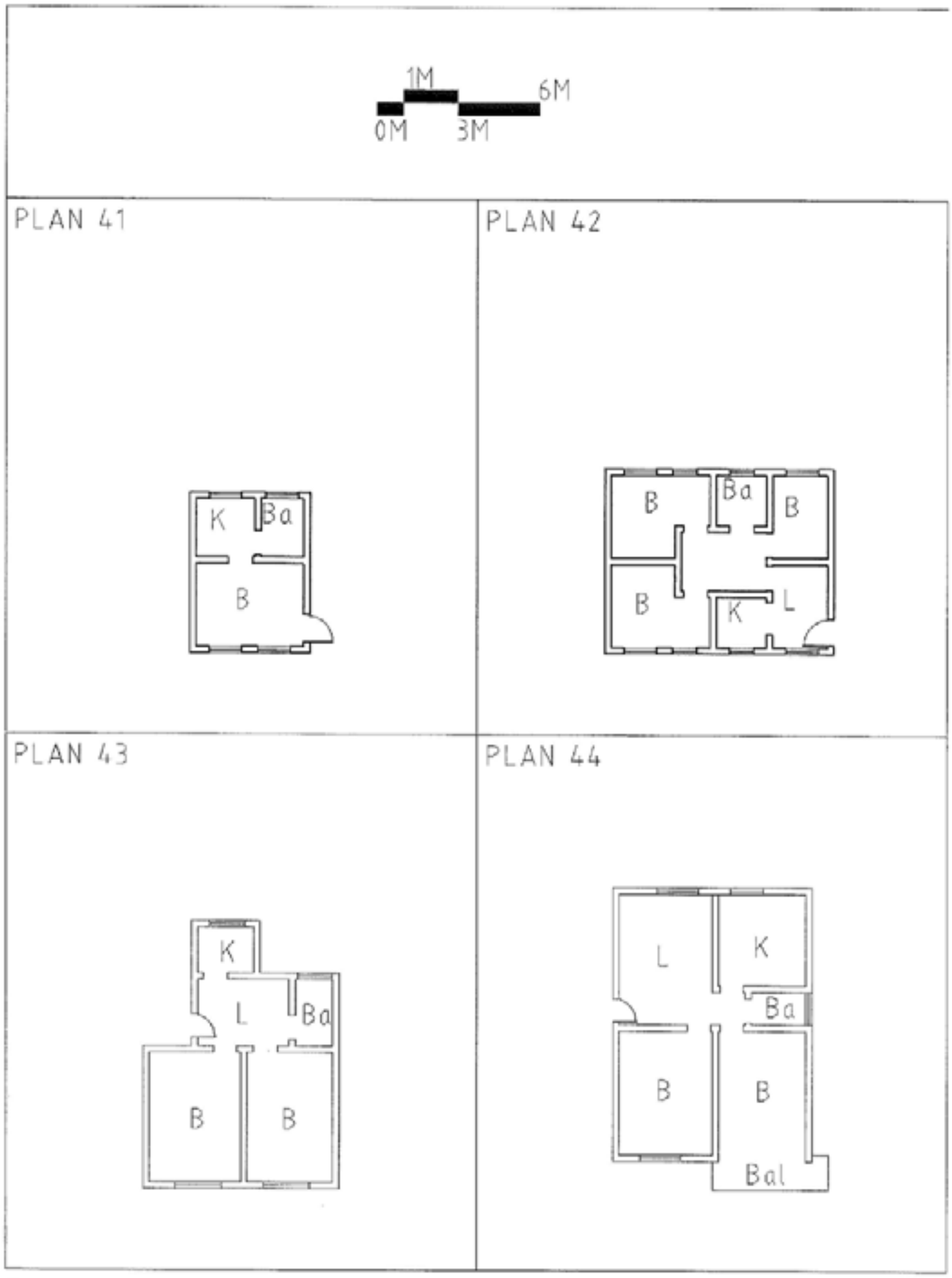
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PLAN 43
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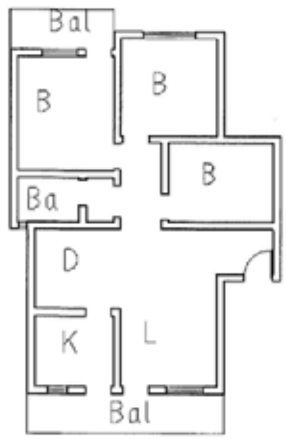
L
Ba
B
B
PLAN 44
L
K
Ba
B
B
Bal

PLAN 45



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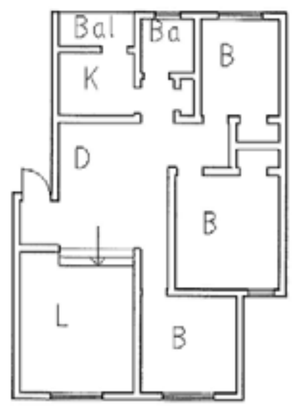

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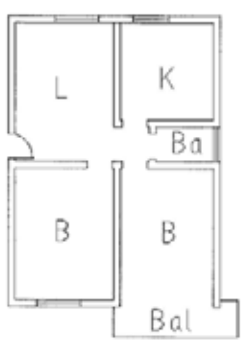

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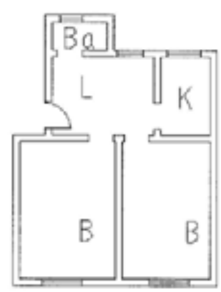

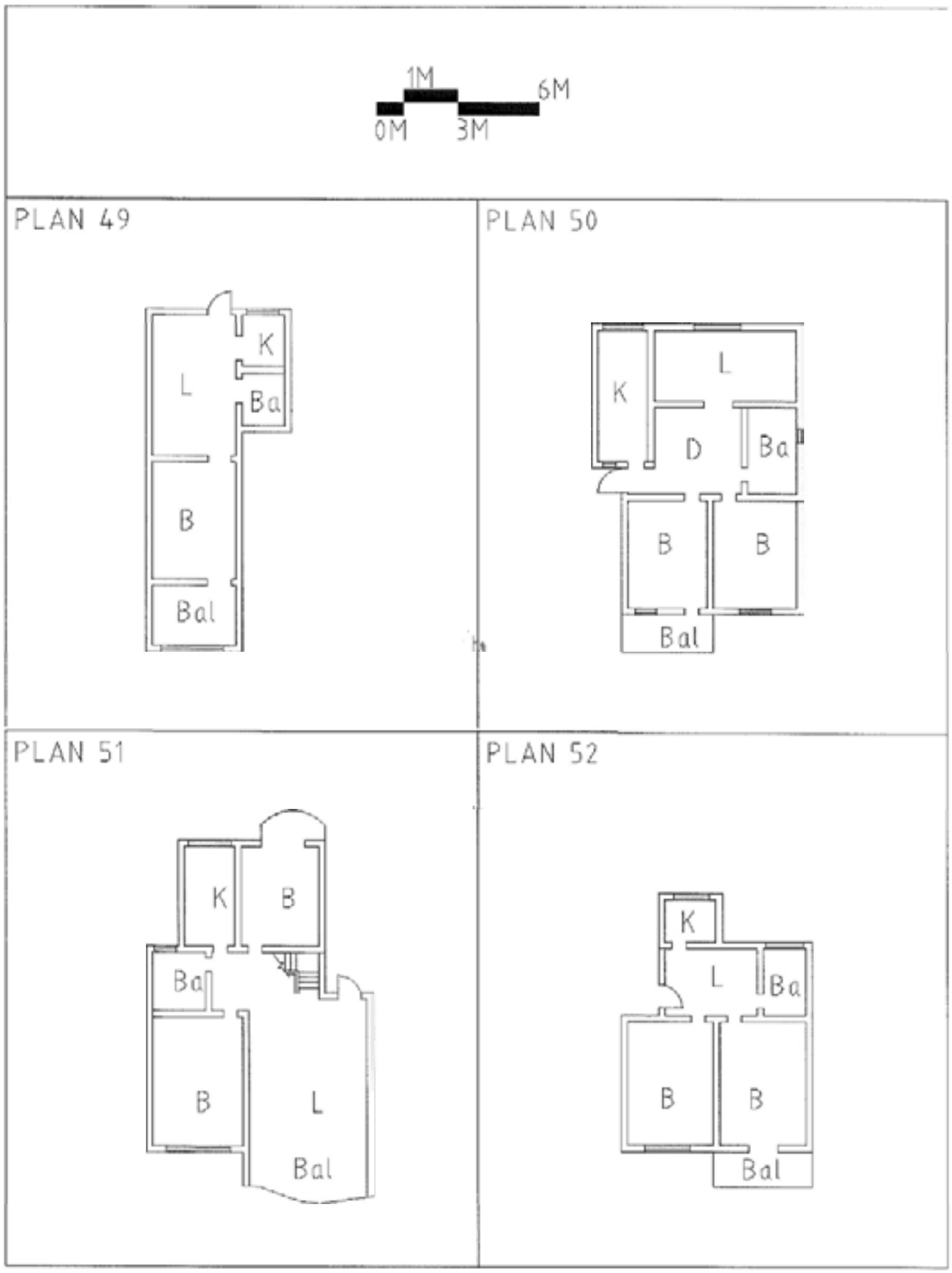
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PLAN 50
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D
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PLAN 51
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B
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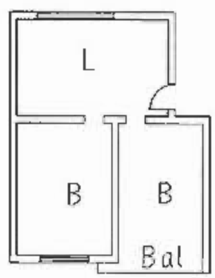
PLAN 52
K
L
Ba
B
B
Bal

PLAN 57



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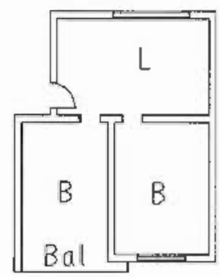

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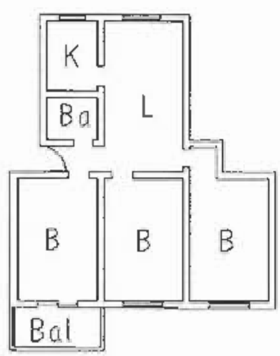

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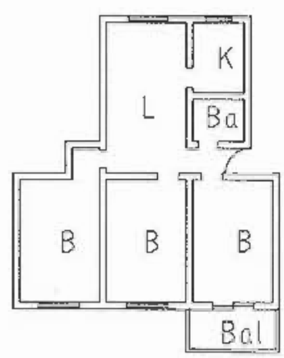

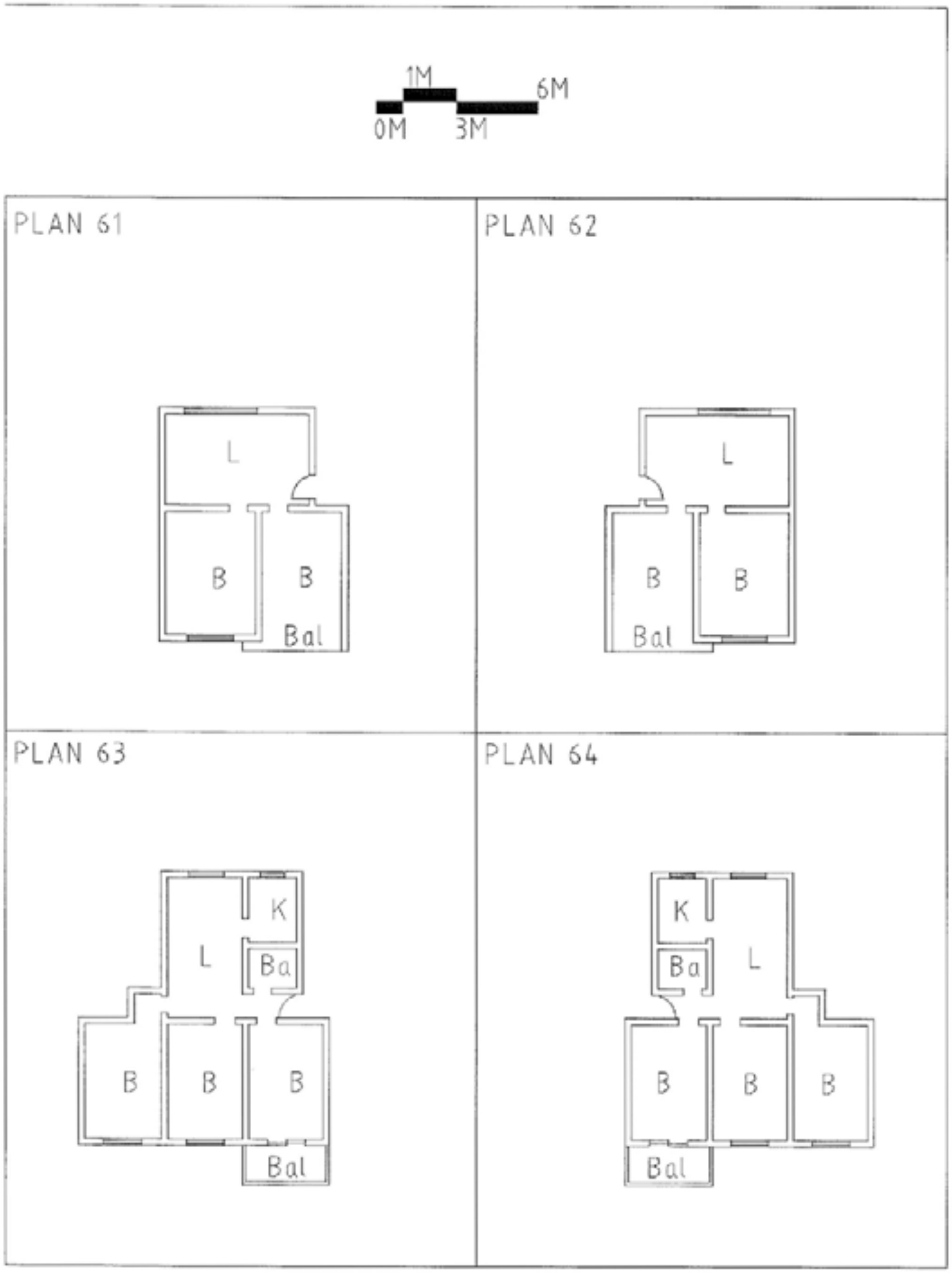
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PLAN 61
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B
Bal
PLAN 62
L
B
B
Bal
PLAN 63
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Ba
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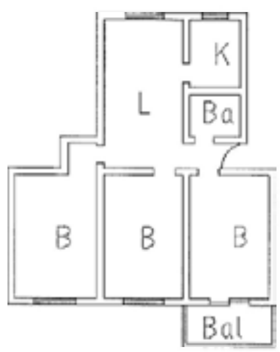
B
Bal
PLAN 64
K
Ba
L
B
B
B
Bal

PLAN 65



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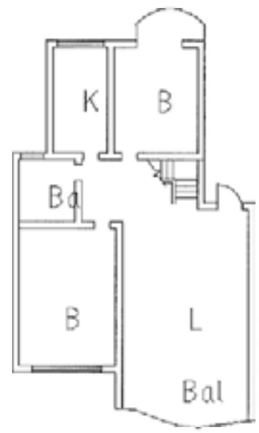

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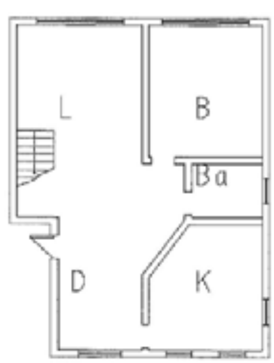

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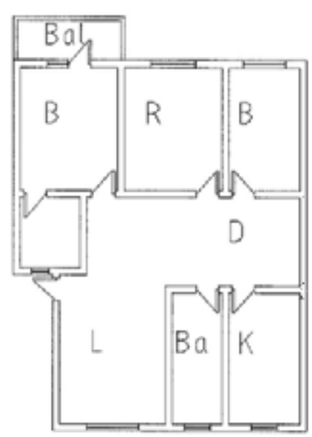

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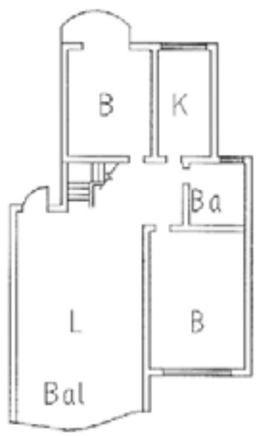

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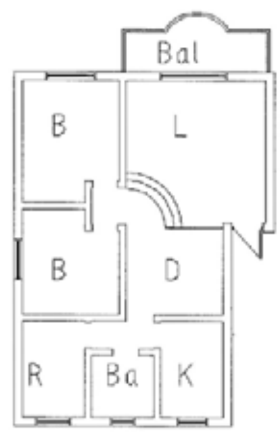
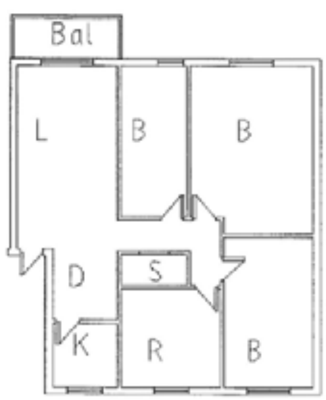


PLAN 71



Appendix G: Cited Equation

Equation 2-1:

$$H\text{-}Ed\text{-}Esw\text{-}Ere\text{-}L=K=R+C$$

H: the internal heat production in human body; It is a function of the activity of the person; H=M(1-η); M: metabolic rate; η=W/M; η: external mechanical efficiency

Ed: the heat loss by water vapor diffusion through the skin; Ed=0.35ADu (1.92ts-25.3-pa)

ADu: body surface area=DuBois area; ts: temperature of skin; pa: vapour pressure in ambient air

Esw: the heat loss by evaporation of sweat from the surface of the skin;

*Esw=0.42 ADu [M/ ADu *(1- η)-50]*

Ere: the latent respiration heat loss; Ere =0.0023M(44-pa)

L: the dry respiration heat loss; L=0.0014M(34-ta)

K: the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing);

R: the heat loss by radiation from the outer surface of the clothed body;

*R=3.4*10-8 ADu*fcl*[(tcl+273)4-(tmrt+273)4]*

fcl: the ratio of surface area of the clothed body to the surface area of nude body

tcl: temperature of cloth; tmrt: the mean radiation temperature

C: the heat loss by convection from the outer surface of clothed body

*C= ADu * fcl*hc*(tcl- ta)*

Source: Fanger, P. O. (1970). Thermal Comfort: Analysis and Applications in Environmental Engineering. New York, McGraw-Hill Book Company: P22-42

Equation 2-3:

$$PMV=(0.352e^{0.042(M/Adu)}+0.032)Load$$

PMV: predicted mean vote of thermal sensation;

M/Adu: internal heat production;

Load: heat load, while Load= H-Ed-Esw-Ere-L -R-C

Source: Fanger, P. O. (1970). Thermal Comfort: Analysis and Applications in Environmental Engineering. New York, McGraw-Hill Book Company: P114

Equation 2-4:

$$Tc = a*Tout+b$$

Tc: comfortable temperature

Tout: outdoor temperature

$Tout=Trm=(1-\alpha)*(T_{od-1}+\alpha*T_{od-2}+\alpha^2*T_{od-3}+...)$

$nTrm=(1-\alpha)*T_{od-1}+\alpha*n\text{-}1Trm$

Tout=Trm: running mean of outdoor temperatures weighted according to their distance in the past

nTrm: running mean temperature for day n and n-1Trm for the previous day. Normally, $\alpha=0.8$

a, b: coefficient and constant

Another calculation for Tout in Netherland is: Tout= (1Ttoday+0.8Tyesterday+0.4Tday before yesterday+0.2Tday before day before yesterday)/2.4

Source: Nicol, F. and M. Humphreys (2007). "Maximum temperatures in European office building to avoid heat discomfort." Solar Energy 81: P298

van der Linden, A. C., A. C. Boerstra, et al. (2006). "Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate." Energy and Buildings **38**(1): P12

Equation 2-5:

$$PMV_{new}=e*M_{adjusted}PMV_{old}$$

PMV_{new} : modified PMV value;

PMV_{old} : PMV value calculated by the old PMV model not addressing thermal adaptation

e: expectance factor; it is estimated to vary between 1 and 0.5: 1-for air-conditioned buildings, 0.5-for warm weather whole year and no air-condition, 0.7-same region but many air-conditioned building, 0.7~0.8-partial season is warm and few buildings with con, 0.8~0.9 same region with many buildings with condition, 0.9~1-brief period is warm;

$M_{adjusted}$: adjustment rate of metabolic rates which should be reduced by 6.7% for every scale unit of PMV above neutral

Source: Fanger, P. O. and J. Toftum (2002). "Extension of the PMV model to non-air-conditioned buildings in warm climates." Energy and Buildings 34(6): P534

Equation 3-1

$$T_{mrt} = \left[\left(t_g + 273\right)^4 + \frac{1.10 * 10^8 * V^{0.6}}{\varepsilon * D^{0.4}} (t_g - t_a) \right]^{0.25} - 273$$

Where ε is emissivity (0.95 for a black globe);
D is globe diameter (0.038m for "ping-pong");
V is air speed in m s^{-1};
t_a is air temperature in ℃;
and t_g is globe thermometer's temperature in ℃.

Source: de Dear, R., Gz. S. Brager, et al. (1997). Developing an adaptive model of thermal comfort and preference. Sydney & Berkeley, Macquarie Research Ltd., Macquarie University & Center for Environmental Design Research, University of California: P42

Appendix H: In-depth Studies Households

1. Family A

Housing characteristics

This apartment was located in a big residential estate in Nanwhu in Wuchang, one of main residential districts in Wuhan (new construction land changed from agriculture). The apartment stood on the third floor of a six-story block and faced to south and north. Gross Floor Area of was 109m^2 and Usable Floor Area was around 100m^2 comprising living room, reading room, bathroom, kitchen, dinning room and two bed rooms. It was a very typical housing unit in the urban area of Wuhan for a three-person family (a child was expected in near future). The whole residential estate was built in 2006 and its envelop design fulfilled the requirements of regional standards for building performance (The Ministry of Construction 2001). This building block was in a linear layout with sufficient daylight. More construction information can be found in the Table H-1, and its plan and field photos are displayed in the Figure H-1.

Table H-1: Construction information of Family A

Building construction time	Located storey / Total storey	Construction and materials of roof, floor, window, door, and walls					Cooling and heating system
		Roof	Windows & doors	Floor	External wall	Internal wall	
2006	3/6	100mm concrete (floor)	Aluminium alloy frame and double-layer glass	100mm concrete	250mm light brick	100mm light brick	Individual air condition

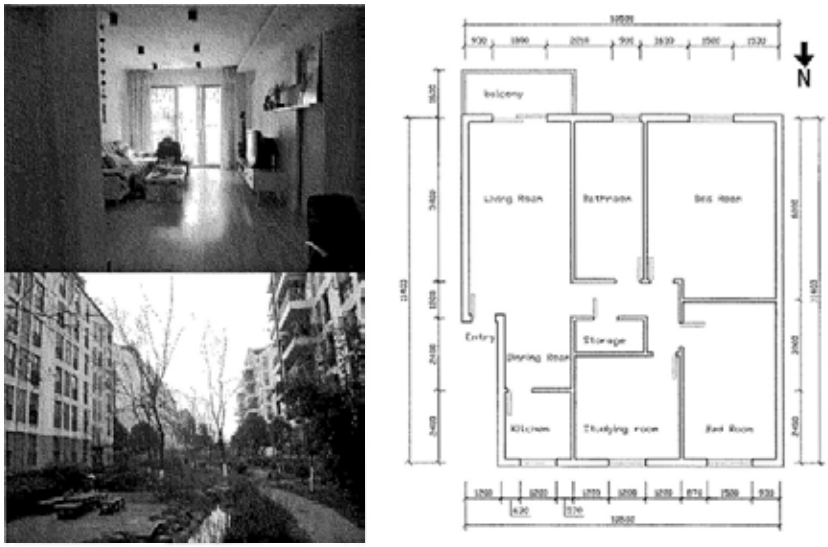


Figure H-1: Field photos and apartment plane of Family A

Economic conditions:

Family A was two-person family of husband and wife. Their monthly income per person was about 7000~8000RMB, which placed this family in the middle-class of local urban residents. Constraints from economic condition should not be very critical for this family. Detailed family member information is displayed in the Table H-2.

Table H-2: Family composition of Family A

	Subject	Age	Occupation	Income/month (RMB)	Duration in HS&CW (year)
1	Husband	32	Architect	8000~10000	6
2	Wife	34	Freelance	5000~8000	34

Living habits:

Family A reported that they usually occupant their apartment at night time. Intermittent and local heating/cooling method was adopted by them when the indoor thermal environment is very severe to carry out planned activity, such as sleeping, working and eating. They changed their clothing closely with weather variations, very heavy clothes in winter (around "2.2clo") and light clothes in summer (around "0.3clo"). Husband expressed that in winter the indoor was much more uncomfortable comparing with his hometown (Heilongjiang Province), but he had been used to the cold and could tolerate it to certain extent. He also explained that electricity bill did not constrain them to use the air-conditioner; actually they were frugal for so many years and just thought it was wasteful to switch on air conditioning if they could tolerate the ambient thermal environments.

2. Family B

Housing characteristics:

Family B's apartment was in a small housing community built in Wuchang for university stuff. This apartment was located in the fifth floor of a seven-storey building facing to north and south. Gross Floor Area was 135m^2 and usable Floor Area was 120m^2 with two bed rooms, one reading room, one bathroom, one kitchen, one living room and dining room. Because this residential estate was built in 2000 before the regional building efficiency standard's establishment, the window design followed the old building code and its thermal performance was not good enough. This building block was also linearly arranged with other blocks with sufficient daylight. More construction information can be found in the Table H-3, and its plan and field photos are displayed in the Figure H-2.

Table H-3: Construction information of Family B

Building construction time	Located storey / Total storey	Construction and materials of roof, floor, window, door, and walls					Cooling and heating system
		Roof	Windows & doors	Floor	External wall	Internal wall	
2000	5/7	120mm concrete (floor)	PVC frame and single-layer glass	120mm concrete	240mm solid brick	240mm solid brick	Individual air condition

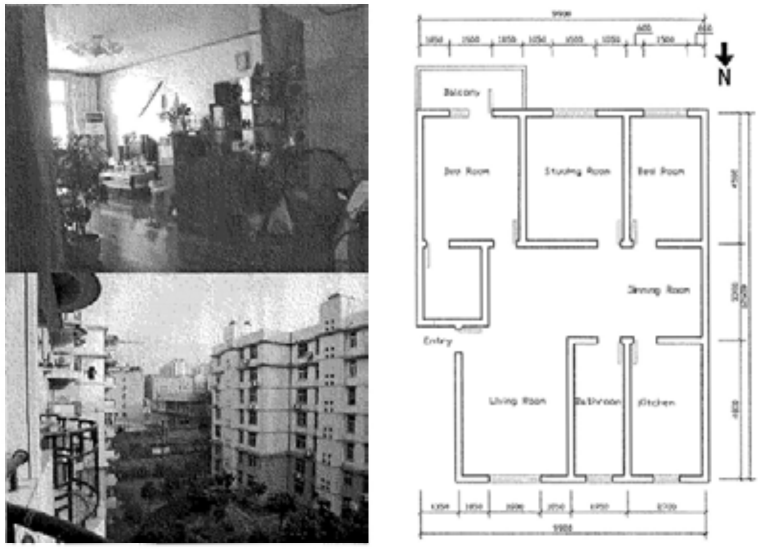


Figure H-2: Apartment plan and field photos of Family B

Economic conditions:

Family B was typical three-person city family. But during the investigation period, the husband was out of town and wife's parents came to Wuhan to live with them. Hence the family composition can be found in Table H-4. From the view of economic condition, it was also a middle class family and they have no heavy living burden. Maximum several hundred [RMB] bill for heating/cooling was not big problem for this family.

Table H-4: Family composition of Family B

	Subject	Age	Occupation	Income/month (RMB)	Duration in HS&CW (year)
1	Wife	34	University teacher	3000~5000	16
2	Husband	34	University teacher	5000~80000	16
3	Daughter	5	Kindergarten		5
4	Grandpa	59	Retired	2000~3000	1~2 months/year (several years)
5	Grandma	61	Retired	800~1500	1~2 months/year (several years)

Living habits:

This three-generation family showed more diversity in terms of living habits related thermal environments. In winter evenings, they usually swithched on air-conditioning for a couple of hours for family activities because of its effectiveness, and then they switched off the air-conditioning and turned on a portable heater in the bedroom for good sleep because they thought it was more healthy. In summer, they would switch on the air-conditioner for cooling as they felt electrical fan can not release their discomfort effectively. The grandparents enjoyed a sunbath during winter and outdoor activities after sunset in summer. Wife reported that she would lower her thermal expectation in winter and summer because she knew the climate very well and could accept it even though she grew up in North China. The 5-year-old daughter seemed have no special actions responding to weather change except for clothing variations with parents' help.

3. Family C

Housing characteristics

Family C located in Qingshan of Wuchan. This house estate actually was one part of a very huge residential district in Wuhan which was originally state-owned unit housing. Now, it had been changed to private-ownership following the whole housing policy reforms. Nevertheless, in this estate, there was some service nobody would like to pay for now because it was stuffs' welfare before. Central heating service was present in this case.

Family C was two-storey apartment built in 2002, therefore the envelope's thermal performance was not good enough either. Gross Floor Area was 135m^2 and usable Floor Area was 120m^2 with three bed rooms, two bathroom, one kitchen, one huge living room and dining room. This building block was also linearly arranged with other blocks with sufficient daylight. More construction information can be found in the Table H-5, and its plane and field photos are displayed in the Figure H-3, H-4.

Table H-5: Construction information of Family C

Building construction time	Located storey / Total storey	Construction and materials of roof, floor, window, door, and walls					Cooling and heating system
		Roof	Windows & doors	Floor	External wall	Internal wall	
2002	1&2/4	120mm concrete (floor)	PVC frame and single-layer glass	120mm concrete	240mm solid brick	240mm solid brick	Individual air condition & central water heating

Figure H-3: Field photos of family C

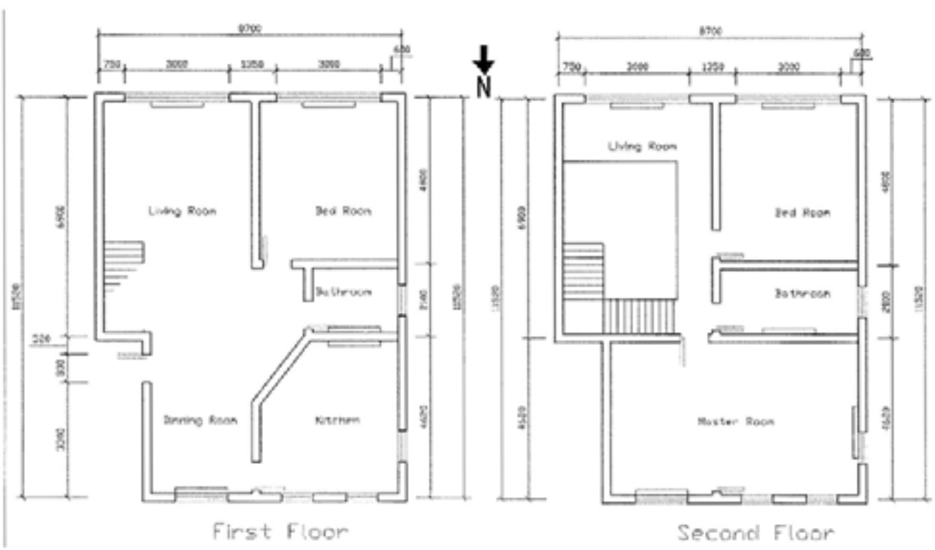


Figure H-4: Apartment plan of Family C

Economic conditions

Family C was one four-person family with three generation including grandpa, mother and the young couple (Table H-6). This family was very special in terms of their heating system in Wuhan. Their apartment was equipped with free central water heating system to benefit the well being of retired leaders in the state-owned company. So the main heating method in winter depended on the central heating. Additionally, their main cooling method in summer was an air conditioner and an electrical fan was rarely used by this family.

Table H-6: Family composition of Family C

	Subject	Age	Occupation	Income/month (RMB)	Duration in HS&CW
1	Grandpa	88	Retired	3000~4000	65
2	Mother	59	Retired	3000~4000	59
3	Son	32	Stock manager	5000~8000	32
4	Son's wife	30	Bank clerk	5000~8000	30

Living habits:

Family C used air conditioner most frequently in all the investigated families. They reported they seldom used fan and always kept air condition on when the room was occupied in summer, and therefore the monthly bill for cooling was always higher than 500RMB. In winter, free central heating guaranteed this family very warm (indoor air temperature was around 22℃) and they were used to take off heavy coat in home keeping around "1.1clo" clothing level. All the family members complained it was too hot and they had to open windows for cooling. Actually, the windows in living room and bathroom were always kept open for fresh air, and windows in bedroom would be opened as necessary.

Additionally, mother said that in Wuhan (HS&CW climatic zone) central heating cooling system was the trend in future because everybody preferred better life and nothing could hold back the peoples' demands for comfortable thermal environments, especially when they had owned it before.

4. Country immigrating households

Six country immigrating households were investigated in this study for comparison with local urban residents. The purpose of this comparison is to investigate occupants' living experience and economic condition's impacts on their adaptive thermal comfort.

Housing characteristics:

This investigated linear bungalow located in the middle of a huge residential district facing a lane connecting several housing estates, and behind there was a market blocking all the natural ventilation and daylight from north as shown in Figure H-5. Investigated families all lived and did business in their individual two-storey units. The ground floor served as working place and living room, and the half-first floor was their bedroom (Figure H-5). During the investigating time, the front doors were opened to the lane and the indoor thermal environments were almost same as outdoors.

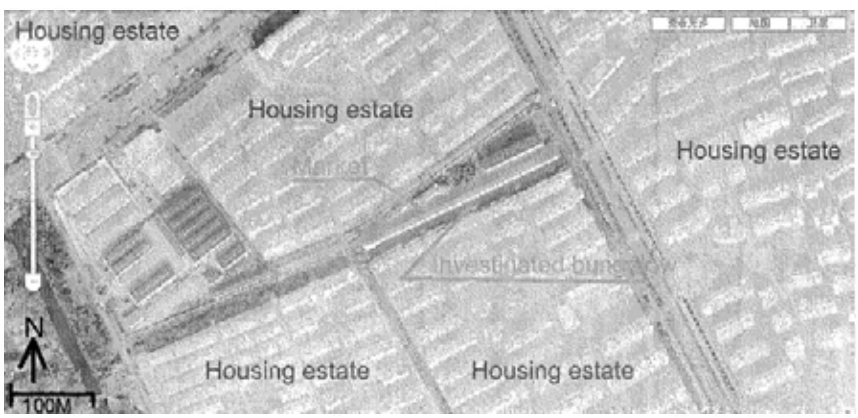


Figure H-5: Location of the bungalow and surrounding housing estates

Because of the extreme hot weather in summer and insufficient natural ventilation, all the investigated families equipped air condition in their "bedroom". Plan of each unit refers to Figure H-6 and field photos are showed in Figure H-7.

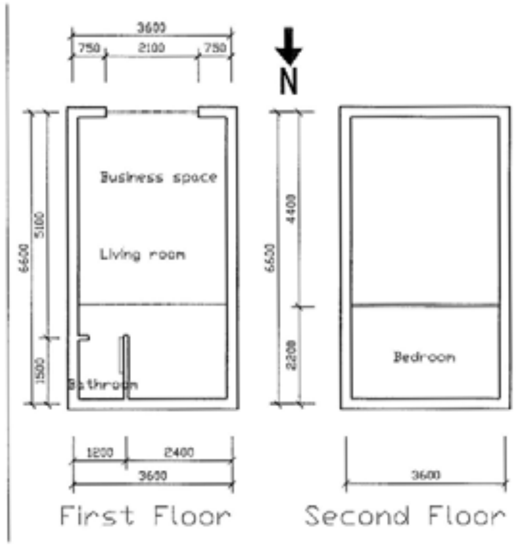


Figure H-6: Apartment unit plan for country immigrants

Figure H-7: Field photos of new immigrants' living space

Economic conditions

Basically, it is assumed that those country immigrants' economic conditions are not very good, not only because of their income but also their heavy living burden. All the investigated families were businessmen and it was very hard to know their income directly. But their living environments could indicate their economic conditions to some extent. They were frugal and tried to minimize the daily expense. Table H-7 gives the composition of investigated new immigrants.

Table H-7: Investigated new immigrants composition

Family	Subject	Gender	Age	Occupation	Duration in HS&CW (years)
Fruit shop	1	female	40	sale	40
	2	male	42	salesman	42
	3	male	20	student	20
Hardware store	4	female	39	sale	39
Reclamation depot	5	male	40	collector	40
	6	male	9	Student	9
	7	female	37	collector	37
Snack bar	8	male	48	Cooker	48
	9	female	46	Cooker	46
Stainless steel shop1	10	male	34	worker	34
Stainless steel shop2	11	female	34	housewife	34
	12	male	37	Worker	37

Living habits:

All the investigated country immigrants were living in the urban residential district with many years' living experience in country area of Hubei Province. Therefore they all knew the local climatic conditions very well. They made life through supplying different services to local residents and most daily activities happened in this tiny unit. In winter, because of the non-obstruction between indoor and outdoor thermal environments, occupants would like to use a furnace to heat locally (Figure H-8). In summer, fans were used frequently during daily time and air-conditioners were employed in night time for sleep.

Figure H-8: Living habits borrowed from country area