DOCTORAL DISSERTATION

Study on adaptive thermal comfort of public buildings with different indoor operation modes in China

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Nomenclature

1. Naturally Ventilated (NV)
2. Air Conditioned (AC)
3. Evaporative Cooling Air Conditioned (ECA)
4. Mixed Mode (MM)
5. Window-to-Wall Ratio (WWR)
6. Solar Radiation (SR)
7. Solar Heat Gain Coefficient (SHGC)
8. Heating, Ventilation and Air Conditioning (HVAC)
9. International Organization for Standardization (ISO)
10. Chartered Institution of Building Services Engineers (CIBSE)
11. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
12. Predicted Mean Vote (PMV)
13. Adaptive Predicted Mean Vote (APMV)
14. Expectative Predicted Mean Vote (ePMV)
15. Predicted Percentage of Dissatisfied (PPD)
16. Actual Percentage of Dissatisfied (APD)
17. Thermal Sensation Vote (TSV)
18. Mean Thermal Sensation Vote (MTSV)
19. Humidity Sensation Vote (HSV)
20. Air Velocity Sensation Vote (ASV)
21. Thermal Preference Vote (TPV)
22. Humidity Preference Vote (HPV)
23. Air Velocity Preference Vote (APV)
24. Thermal Acceptability Vote (TAV)
25. Humidity Acceptability Vote (HAV)
26. Air Velocity Acceptability Vote (AAV)
27. Overall Comfort Vote (OCV)
28. China Meteorological Administration (CMA)
29. Relative Humidity (RH)
30. Operative Temperature (T_o)
31. Globe Temperature (T_g)
32. Mean Radiant Temperature (MRT)
33. Effective Temperature (ET)
34. Standard Effective Temperature (SET)
35. Neutral Temperature (T_n)

36. Preference Temperature (T_p)
37. Comfort Temperature (T_c)
38. Prevailing Mean Outdoor Temperature (T_{pma})
39. Griffiths Constant (G)
40. Standard Deviation (SD)
41. Determining Coefficient (R^2)
42. Clothing Insulation (CI)
43. Body Superficial Area (BSA)
44. Body Mass Index (BMI)
45. Metabolic Rate (MR)
46. Skin Vapor Diffusion (E_{sv})
47. Heat Loss by Sweat Diffusion (E_{sd})
48. Heat Loss by Latent Respiration (E_{lr})
49. Heat Loss by Dry Respiration (E_{dr})
50. Mean Skin Surface Temperature (T_{sk})
51. Severe Cold Zone (SCZ)
52. Cold Zone (CZ)
53. Hot Summer and Cold Winter Zone (HSCW)
54. Hot Summer and Warm Winter Zone (HSWW)
55. Mild Zone (MZ)

Study on adaptive thermal comfort of public buildings with different indoor operation modes in China

Abstract

Thermal comfort plays a significant role on building indoor environment, it is defined as the state of mind in which occupants satisfied with surrounding environment according to American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE-55). People working efficiency will also be increased by 15% in that status. Therefore, how to pursue the unity of energy conservation and thermal comfort has become an urgent issue in contemporary society.

Generally speaking, the study for thermal comfort can be classified as static and adaptive approach. Fanger's Predicted Mean Vote (PMV) model is based on steady-state heat transfer theory that takes the six body/environmental parameters into consideration. However, it is found not to be an appropriate way to calculate the actual situation as it ignores the ability of occupants' adaptability. Adaptive comfort approach, which focused on the people-environment interaction and takes the occupants' natural tendency of adapting changes in thermal environment as well as restore whom comfort into account, has been regarded as a reasonable and accuracy way. Hence, this study by adopting the methods of qualitative subjective survey and quantitative objective measurements, simulation study and regression analysis to carried out a series of investigation studies for public buildings in China's different climate zones.

In chapter 1, the background is firstly elaborated. In addition, the development status of thermal comfort were reviewed. And then proposed the target of the research based on the questions raised.

In chapter 2, the two main research ideals (adjustment PMV model and adaptive comfort model) of the adaptive approach is presented. And focused on the adaptive model, three aspects namely field investigation, climatic adaptability and application are reviewed, respectively.

In chapter 3, the research methodology is expounded. Firstly, two approaches for climate classifications are introduced. In addition, the establishment of adjustment PMV model and adaptive model are explained. Lastly, combined with the evaluation indexes extracted, the whole research process is described in detail.

In chapter 4, based on adaptive comfort model approach, a systematic investigation is conducted for public building standard rooms with evaporative cooling air conditioned system (ECS) in Urumqi (China). Meanwhile, the authentic indoor physical environment and actual thermal comfort are surveyed. Through the regression analysis, the neutral (comfort) temperature, preference temperature and acceptable temperature range in ECS buildings are determined, respectively. Ultimately, the adaptive model is established by using the relationship between outdoor prevailing mean temperature and indoor comfort temperature.

In chapter 5, based on adaptive comfort model approach, a pilot study is further unfolded for different indoor operation modes between evaporative cooling air conditioned and naturally ventilated buildings in Turpan (China). The differences of selective behavior adjustment are concluded. Meanwhile, verified the accuracy of recommended models in ASHRAE-55, EN 15251 and Chinese GB/T 50785 comparing to each modes.

In chapter 6, based on adjustment PMV model approach, the optimization of various parameters for Chinese climate zones are carried out with consideration of energy demands and adaptive thermal comfort by simulation study. To be specific, five typical benchmark cases with climatic adaptability are established. At the same time, with the help of numerical calculation, a further coupling calculation of indoor adaptive thermal comfort is conducted to search for the best thermal range with less energy consumption.

In chapter 7, the conclusions of the whole thesis is summarized and the future work of adaptive thermal comfort is discussed.

Keywords: Indoor thermal environment; PMV; Adaptive comfort model; Public building; Energy consumption

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Chapter 1

INTRODUCTION AND PURPOSE OF THE RESEARCH

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CHAPTER 1 INTRODUCTION AND PURPOSE OF THE RESEARCH 1-1

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1.1 Background

The severe energy situation is a common issue faced by the whole world at the moment. According to Chinese building energy consumption report, as shown in Fig.1-1, the global terminal energy consumption of building sector was approximately 4124 million tons of coal equivalents (Mtce) that accounted for 30.63% of the total demand in 2017. Among the various countries, China's total building consumption was 670 Mtce, ranked the second [1].

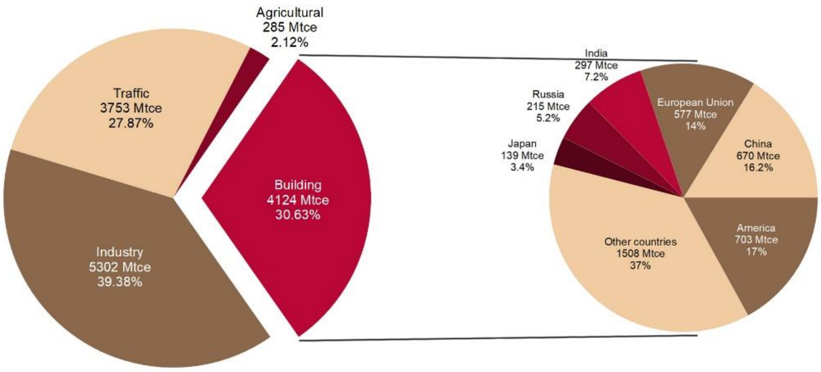


Fig. 1-1. Proportion and regional distribution of global building terminal energy [1].

In Fig.1-2 and Fig.1-3, it can be observed that the energy utilization for public buildings in China occupied the larger part (nearly 40%) than urban and rural residential buildings [2]. Furthermore, the requirement value had also increased from 118 Mtce in the year of 2001 to 364 Mtce in 2017 for public buildings and was projected to continue growing. While the percentage of total energy demand for each type kept steady. The primary reasons mainly lie upon two aspects as following, for one thing, it was caused by the rapid growth of population and per capita building area; for another, the spread of heating, ventilation and air conditioning (HVAC) system consumed approximately 50% of building energy in more than half a century when it was widely used [3].

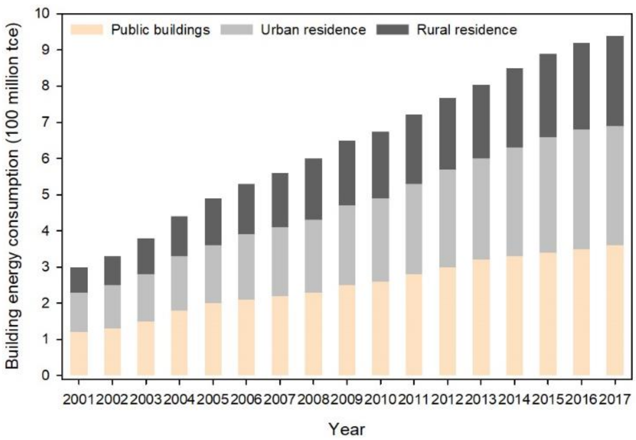


Fig. 1-2. Building energy variation in China: 2001-2017 [2].

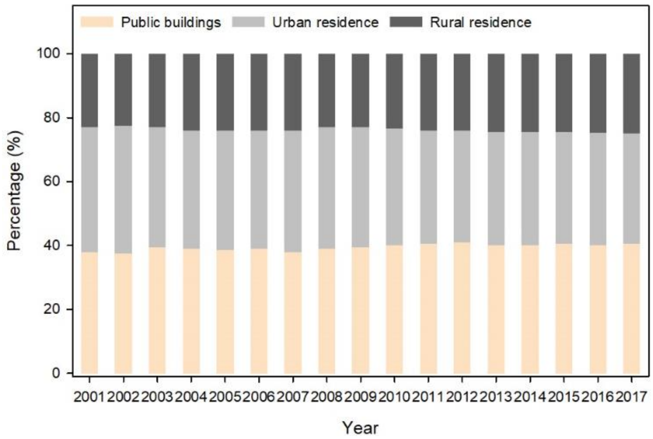


Fig. 1-3. The proportion of energy consumption for different building types [2].

In the design and usage stage of HVAC, the most significant issue is how to determine the appropriate indoor environmental parameters based on the requirements of human thermal comfort level, which have a decisive impact on building energy consumption. According to relevant statistics, a higher temperature set point was considered as an appropriate strategy to decrease energy demand during cooling period [4]. Take Beijing as an example, with the indoor setting temperature raised from 24℃ to 28℃ in summer, the entire cooling period obtained from simulation will be shorted by 22%, and the maximum cooling loads can also be reduced by 15% [5]. In winter, 20%~40% can be saved by adopting the recommended temperature of 18℃ compared with the comfortable temperature of 22℃[6]. Therefore, the standard of thermal comfort determined energy consumption and was also a critical factor for creating a healthy and effective workplace.

At present, several influential global standards had been established for evaluating the indoor thermal environment, such as ASHRAE-55 [7], ISO 7730 [8] and EN 15251 [9], which the calculation results were both based on the predicted mean vote (PMV) model proposed by P.O. Fanger through artificial climate laboratory research. Meanwhile, professor Gagge also carried out the concept of effective temperature (ET*) and standard effective temperature (SET) according to the two-node human thermoregulation model [10]. The common characteristics of above models were believe that environmental parameters do not change with the time variation, and regarded the human body as a passive recipient of external thermal stimuli. In other words, these steady-state thermal comfort models specified a relatively narrow comfort zone. Nevertheless, numerous field investigations of the actual building environment were conducted in recent years and indicated that in some specific or non-air conditioned indoor working conditions, the deviation was often occurred between PMV model and authentic thermal sensation (TSV). Compared with values predicted by PMV, the actual thermal sensation was closer to neutral status, and the acceptable temperature range of human body was wider than predicted results. Such findings prompted researches to re-examine the rationality of steady-state PMV model's application.

In view of afore-mentioned deviation (PMV against TSV), adaptive comfort approach, which focused on the human-environment interaction and taken the occupants' natural tendency of adapting changes in thermal environment as well as restored whom comfort into account, had been regarded as reasonable and accuracy in recent years [11-12]. Generally speaking, human adaptability mainly including behavioral adaption, psychological adaption and physiological adaption. Behavioral adaption referred to consciously or unconsciously taking behaviors that change one's own thermal equilibrium state, which divided into auto-adaptive actions (i.e. transform clothing levels), technical regulation (i.e. adopting shading measures, raise/lower the design temperature of HVAC and open/close windows etc.) and cultural habits (i.e. taking naps to lower the metabolic rate). Psychological adaption was a transformation in sensory response based on thermal experience or preference, it could resulting the optimal comfort value differ from actual setting temperatures. Physiological adaption referred to the regulation of blood vessels by constriction/dilation and sweat secretion under the control of thermoregulation center, which containing genetic adaption (between the two generations) and environmental adaption (within individual whole lifetime). In 2001, Fanger summarized the field surveys results by de Dear et al. of naturally ventilated buildings in Bangkok, Singapore, Athens and Brisbane, observed that the phenomenon of “scissor difference” occurred between predicted mean vote (PMV) and actual thermal sensation (TSV) [13], as shown in Fig.1-4. The higher indoor temperature, the larger that deviation. The findings suggested that the actual thermal tolerance of the subjects was higher than predicted values, meanwhile, people's acceptance of dynamic environment is obviously higher than that of artificial control condition. Multiple studies had also revealed that the occupants' comfort requirements in different countries were varying from each other, as listed in Table 1-1. American's comfort temperature was 3°C higher than England, and in the tropics, the preference temperature was the highest that approximately of 25-27°C. People who lived in cold regions for long periods of time were more adapted to lower ambient temperatures, and the opposite situation was appeared in tropic and sub-tropic areas.

China is a vast geographical area from south to north with different climate conditions, adding with different living habits and unbalanced economic development, which would resulting the deviation between occupants' physiological adaption and psychological expectation to the thermal environment. Thermal comfort is a fuzzy collection with not clearly boundaries, in order to make an accurate evaluation of environmental tolerance, it is not only necessary to understand the age, gender, clothing, behavior style, cultural and social background of the individual in the thermal environment, but also should focus on the ability to adapt to changes in the long-term selection process [14]. Therefore, as for the research of thermal comfort in China, it is not reasonable to fully compliance with current international standards. In other words, only by fully consideration of the climatic adaptability and conducted on the field investigation can obtain a more accurate and objective evaluation model in the actual situation.

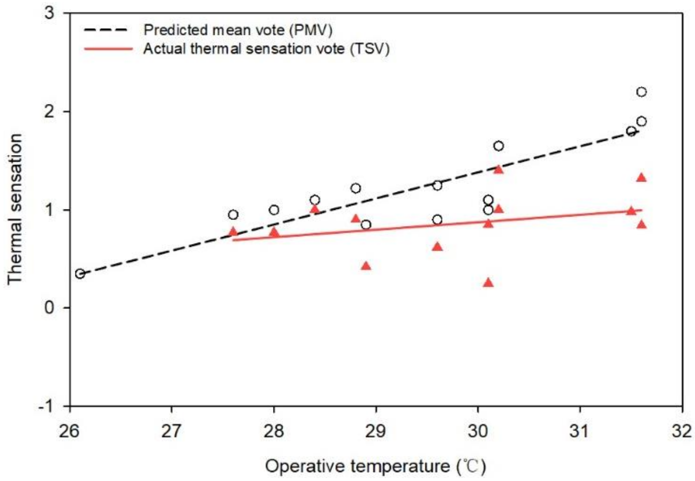


Fig. 1-4. PMV against TSV in non-air conditioned buildings during investigation period [13].

Table 1-1. Effective temperature (ET) range in different countries (80% base line).

Location/	England		America		Australia	Singapore	Tropics
Index	Summer	Winter	Summer	Winter	All year	All year	All year
$ET_{min.}$	--	14℃	18℃	15℃	--	24℃	22℃
$ET_{comf.}$	18℃	17℃	22℃	20℃	22℃	--	25℃
$ET_{max.}$	22℃	20℃	26℃	23℃	25℃	27℃	27℃

As mentioned above, the adaptive thermal comfort models used by foreign scholars still have some limitations. In order to deeply understand the mechanism of thermal adaptability and better grasp its regularity, this study aimed to develop a series of field investigations and data analysis to explore the various influential factors to human adaptability. Meanwhile, modify and improve the current domestic and international standards according to the related research, thereby to achieve the real unity of energy saving and thermal comfort.

1.2 Development status of thermal comfort

In accordance with the explanation from American society of heating, refrigeration and air conditioning engineers (ASHRAE-55), thermal comfort is a psychological state in which occupants are satisfied with the physical environment [7]. The field of physiology considered that body's thermal regulation function was in the lowest activity level when occupants are in comfort state [15]. Since the popularization of air conditioning technology, numerous researchers had gradually deepened their exploration of the thermal comfort. In this section, on the basis of systematic summary of the main influencing factors, the two significant development stages of the thermal comfort were introduced which mainly referred to static and dynamic approach. Fig.1-5 shows the overall historical process and the specific content are as following.

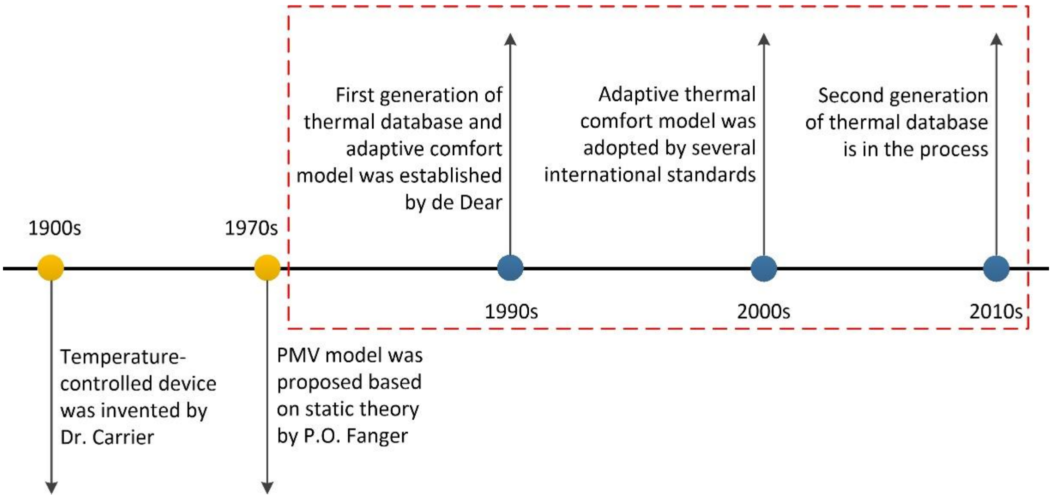


Fig. 1-5. Historical progress of thermal comfort research.

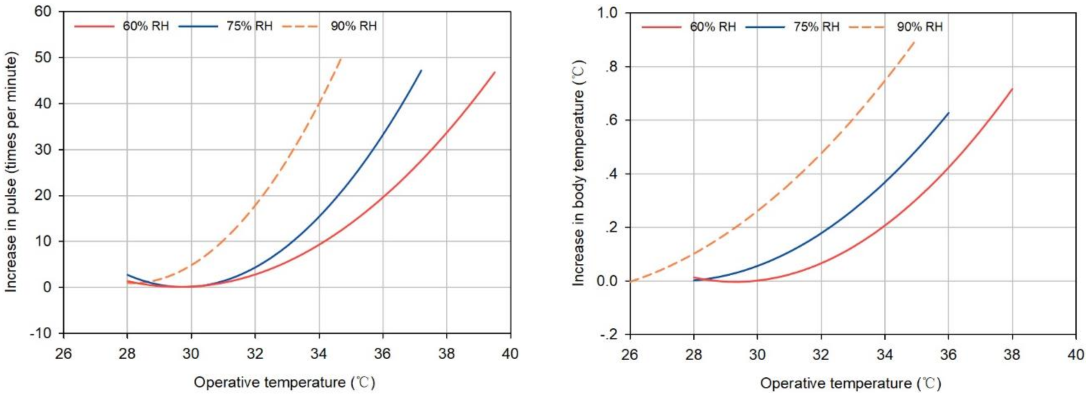
1.2.1 Impact factors of thermal comfort

1) Air temperature

Indoor air temperature is an important index which affects the heat exchange between human body and surrounding environment. Under the condition of constant water vapor pressure and air velocity, the responses of human to the higher ambient temperature is mainly manifested as the increase of skin temperature and perspiration rate. On the contrary, they could reduce heat loss by strengthening metabolism rate in colder condition. According to relevant statistics, occupants' working efficiency would be highest when the air temperature was approximately 25℃, and it would be decreased sharply when temperature lower than 18℃ or higher than 28℃ [16]. Physiological hygiene took 12℃ as the lower limit of building thermal environment.

2) Relative humidity

Relative humidity is the ratio of the actual amount of water vapor in the air to its fullness at the constant air temperature and atmospheric pressure. RH has a significant effect on body's heat balance and thermal sensation, especially in the condition of higher and lower temperature conditions. In warmer environment, the body mainly relies on evaporative heat dissipation to maintain heat balance, a higher RH could prevent sweat from evaporating and lead to a loss of balance. In Fig.1-6, it can be found that in higher temperature conditions, the body temperature and pulse would increase with the higher RH. In colder situation, increasing of RH could accelerate body heat dissipation, at that time, the thermal radiation of body was absorbed by the steam in the air. Meanwhile, the thermal conductivity of clothes would be increased after absorbing water in humid environment, resulting the body feel much colder. Therefore, either higher temperature with higher RH or lower temperature with lower RH is harmful to health, but the effect is not significant when temperature is moderate.



(a) (b)

Fig. 1-6. Influence of relative humidity on pulse (a) and body temperature (b).

3) Air velocity

Air velocity mainly affected human body in two ways, which including the convective and evaporative heat transfer, respectively. The uncomfortable feeling directly caused by air flow is namely "draft sensation" which actually described as a sense of cold feelings. As the environmental temperature is higher than the skin temperature, the air flow would promote the body to absorb more heating from surrounding environment, which can have a negative impact on body's thermal balance. In the situation of low temperature with high humidity, it may cause overcooling due to the excessive heat dissipation if the air velocity with higher values. Also, inappropriate blowing in the warm environment would resulting discomfort such as skin tightness, blocked breathing and even dizziness. Therefore, a proper air speed could compensate for the discomfort caused by temperature and relative humidity.

Research on the coupling effect of airflow and thermal comfort originated in the United States since 1980s. Berglund et al. [17] firstly studied the relationship between air motion and thermal radiation. Afterwards, Scheatzle et al. [18] et al. observed that the upper limit of reasonable air velocity should be increased for higher humidity conditions. In 1989, Fanger et al. [19] took turbulence as a variable representing the air turbulence and summarized the formula for calculating the dissatisfaction rate caused by draft sensation, as listed in Eq. 1-1.

$$PD=(34-T_a)\times(V_a-0.05)\times 0.62\ (0.37\ V_a T_u+3.14) \qquad (1\text{-}1)$$

where PD is percentage of dissatisfaction, T_a is air temperature (℃), V_a is air velocity (m/s), T_u is the turbulence intensity. And the model was adopted in ASHRAE-55 since 1992.

4) Mean radiant temperature

Anything with a temperature above absolute zero will generate heat radiation. Mean radiant temperature (T_{mrt}) is a rather complicated concept, it is a parameter that described environmental characteristics which related to indoor air temperature, black globe temperature and air flow rate. In other words, it is an average value of each surface temperature that affected human body's radiant heat transformation. Houghten et al. [20] discovered that 1°C change in T_{mrt} could lead to 0.5°C and 0.75°C variation in effect temperature (ET) and air temperature (T_a), respectively. The calculation of T_{mrt} is based on the following equations, from which Eq. 1-2 is in natural convection and Eq. 1-3 is in forced convection.

$$T_{mrt}=[(T_g+273)^4+0.4\times10^8(T_g-T_a)^{1.25}]^{0.25}-273 \qquad (1\text{-}2)$$

$$T_{mrt}=[(T_g+273)^4+2.5\times10^8\times V_a^{0.6}(T_g-T_a)]^{0.25}-273 \qquad (1\text{-}3)$$

where T_g is indoor black globe temperature (℃), T_a is air temperature (℃), V_a is air velocity (m/s).

5) Metabolic rate

Due to the physical activity produced heating inside the body, the metabolic rate (MR) directly affected heat exchange between human body and surrounding environment. MR was influenced by a variety of elements, such as muscle activity intensity, environmental temperature, eating time, degree of nervousness, gender and age etc. Also, it was directly proportional to the activity intensity, and varied over a wide range with the individual differences. The energy metabolic rate of a sitting person was defined as 1 met (58W/m^2) to the basic unit, the general values of energy metabolic rate under continuous activities are presented in Table 1-2.

Table 1-2. Energy metabolic rate of human body in variable activities.

Activity state	Category	W/m^2	met
Low-level	Sleeping	40	0.7
	Lying	45	0.8
	Sitting	58	1.0
	Typing	64	1.1
	Relaxed Standing	70	1.2
Moderate-level	Driving	58-115	1.0-2.0
	Cooking	115	2.0
	Cleaning	128	2.2
	Waking	150	2.6
High-level	Tennis	232	4.0
	Basketball	336	5.8
	Hiking	348-406	6.0-7.0
	Running	464	8.0

6) Clothing insulation

Clothing insulation is an important medium of heat and humidity exchange between body and environment. Under the normal and constant body temperature, only 10% of the produced heating would leave the body through breathing, and the remaining 90% needed to be left with the help of skin and clothing [21]. Clothing adjusted the heat and humidity between human body and environment, so that a comfortable microclimate could be created between clothes and skin. To simplify the calculation process, Gagge [22] firstly introduced that concept to explain the total heat transfer resistance between body and environment. Afterwards, P.O. Fanger considered clothing insulation as an important parameter of the thermal comfort into PMV model.

7) Barometric pressure

In general, the daily barometric pressure fluctuated in a narrow range and had less significant impact on human comfort. However, as the pressure obviously lower or higher than normal values, the weight impact of which would increase. For instance, in plateau regions, the lower pressure increased the amount of heat loss from skin evaporation and respiratory exhaust. It is worthwhile mentioning that, the relationship between the increase of latent heat loss and air pressure at lower conditions had not been determined, and none of the correction factors had been proposed at present [19]. On the contrary, a higher pressure could inhibited the evaporative heat dissipation of the skin, which also leading a transient imbalance in heat exchange.

8) Age

Due to the age affected individual body function and behaviors to a certain extent, there would be differences in the performance of thermal comfort. S.S. Korsavi et al. [23] suggested that children's thermal comfort temperature was 1.9K and 2.8K lower than that of adults during non-heating and heating seasons, respectively. Meanwhile, they had lower comfort temperature and higher sensitivity to temperature changes during heating seasons, which mainly attributed to lower practice of personal behaviors and more consistent indoor conditions. J. Yu [24] discovered that there were deviations in the thermal sensation, satisfaction and expectation of older people in mid-season, and they preferred a neutral warm environment, a more narrow comfort interval was obtained by $-0.2 < TSV < +0.2$ based on the calculation of acceptable temperature range.

9) Gender

The experiment by Fanger [25] showed that the men preferred warmer environments than women, but the difference was not statistically significant. J.R. Mcnall [26] also confirmed that there was little difference in comfort requirement between men and women at the three activity levels with standard clothing of 0.6clo, and the actual observed comfort differences between the gender were mainly caused by the variation in clothing level. Although the gender was not the key factor on human thermal comfort, the specific circumstances should be treated differently.

10) Physiological effect

From the view point of physiology, the basic metabolic rate of women was slightly lower than that of men, which could be inferred that women would like a slightly higher temperature. Human body's temperature was characterized by circadian changes, with the maximum and minimum values were appeared at a certain time before sleeping and waking up. Although the temperature variation was existed in actual conditions, which had less impact on thermal comfort.

11) Psychological effect

Energy was always being exchanged between human body and surrounding environment. Although the environment cannot influence the psychology continuously, it has a subtle effect. Due to the variation in psychological quality, expectation and adaptability, occupants may have different feelings towards the same environment, thereby resulting the comprehensive evaluation on thermal comfort were variating from each other. Since the people had psychological preference about the environment, it was easier to satisfy themselves due to the lower expectations.

As afore-mentioned, thermal comfort as a subjective index, is the coupling results that affected by numerous factors. From which the air temperature (T_a), relative humidity (RH), air velocity (V_a), mean radiant temperature (T_{mrt}), metabolic rate (MR) and clothing insulation (CI) were considered to be with higher weight. With advancement of the research in recent years, other factors such as psychological and physiological effects were also taken into consideration seriously.

1.2.2 Static theory of thermal comfort

In order to maintain a normal body temperature, heat production and dissipation must be in balance, from which the metabolic heat generation was the result of biochemical stage, while the heat dissipation was a physical process. The specific expression is shown as Eq. 1-4.

$$f\,(M, I_{cl}, T_a, T_{mrt}, P_a, V_a, T_{msk}, E_{rsw}) = 0 \qquad (1\text{-}4)$$

where M is metabolic rate (W/m^2), I_{cl} is clothing insulation (clo), T_a is air temperature (℃), T_{mrt} is mean radiant temperature (℃), P_a is water vapor pressure (mmHg), V_a is air velocity (m/s), T_{msk} is mean skin temperature (℃) and E_{rsw} is evaporative heat loss (W/m^2).

It can be observed that three conditions were essential for maintaining comfort state: 1) total heat storage of the human body was zero; 2) the mean skin temperature of the body should be stabilize within a narrow range; 3) evaporative heat loss through perspiration need to be moderate. On that basis

P.O. Fanger [25] proposed the relationship between predicted mean vote (PMV) and heat transformation which takes the six body/environmental parameters (T_a, RH, V_a, T_{mrt}, MR, CI) into account, with the calculation process listed as Eq. 1-5.

$$PMV = (0.303e^{-0.036M} + 0.0275)\{(M - W) - 3.05 \times [5.733 - 0.007(M - W) - P_a] - 0.42(M - W - 58.15) - 0.0173M\,(5.87 - P_a) - 0.0014\,(34 - T_a) - 3.96 \times 10^{-8} F_{cl}\,[(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] - F_{cl}\,h_c\,(T_{cl} - T_a)\} \qquad (1\text{-}5)$$

where M is metabolic rate (W/m^2), W is the total amount of human work (W/m^2), P_a is water vapor pressure (mmHg, 1mmHg＝133.322P_a), T_a is air temperature (℃), T_{cl} is mean surface temperature of cloths (℃), T_{mrt} is mean radiant temperature (℃), h_c is convective heat transfer coefficient [$W/(m^2 \cdot ℃)$] and F_{cl} is clothing area coefficient ($F_{cl} = 1 + 0.3I_{cl}$).

The index of PMV adopted ASHRAE seven-point scale (-3 to 3) to describe the human thermal sensation, as is shown in Fig.1-7.

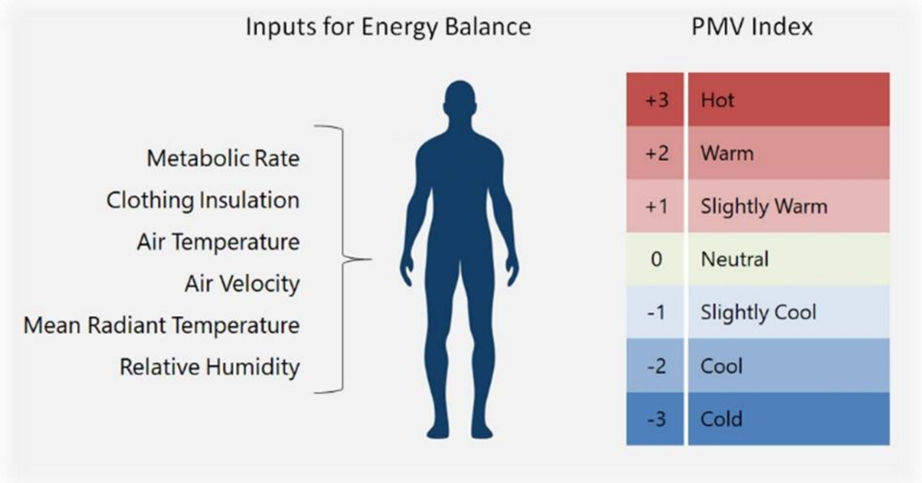


Fig. 1-7. Inputs for energy balance and index classification.

It is worthwhile pointing out that, PMV represented the thermal sensation of the majority of occupants in target environment. However, due to the deviations among individuals, which may not reflected the objective situations all the time. Predicted percentage of dissatisfied (PPD), as another evaluation indicator, was proposed by Fanger to illustrate the frequency of dissatisfaction rate to the actual environment. The quantitative relationship between PMV and PPD is presented as Eq. 1-6. And from Fig.1-8, it can be seen that when PMV equaled zero (neutral state), there were still 5% of the occupants were not satisfied with current environment.

$$PPD = 100 - 95\exp[-(0.03353PMV^4 + 0.2179PMV^2)] \qquad (1\text{-}6)$$

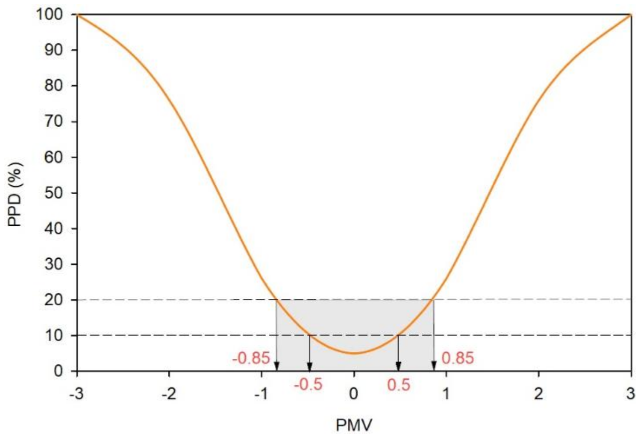


Fig. 1-8. The relationship between PMV and PPD.

Several international standards were formulated based on PMV-PPD index to explore the appropriate environmental parameters that could basically meet the comfort requirement. For instance, ASHRAE-55 carried out the recommended comfort zone in air-conditioned buildings by adopting PMV within ±0.5 (PPD＝10%) [7], as shown in Fig.1-9. In summer, as the relative humidity of 50% and clothing insulation of 0.5clo, the recommended operative temperature could within the range of 24-27℃ (blue shaded area); and in winter, as the relative humidity of 50% and clothing insulation of 1.0clo, which interval was 20.5-24.5℃ (orange shaded area).

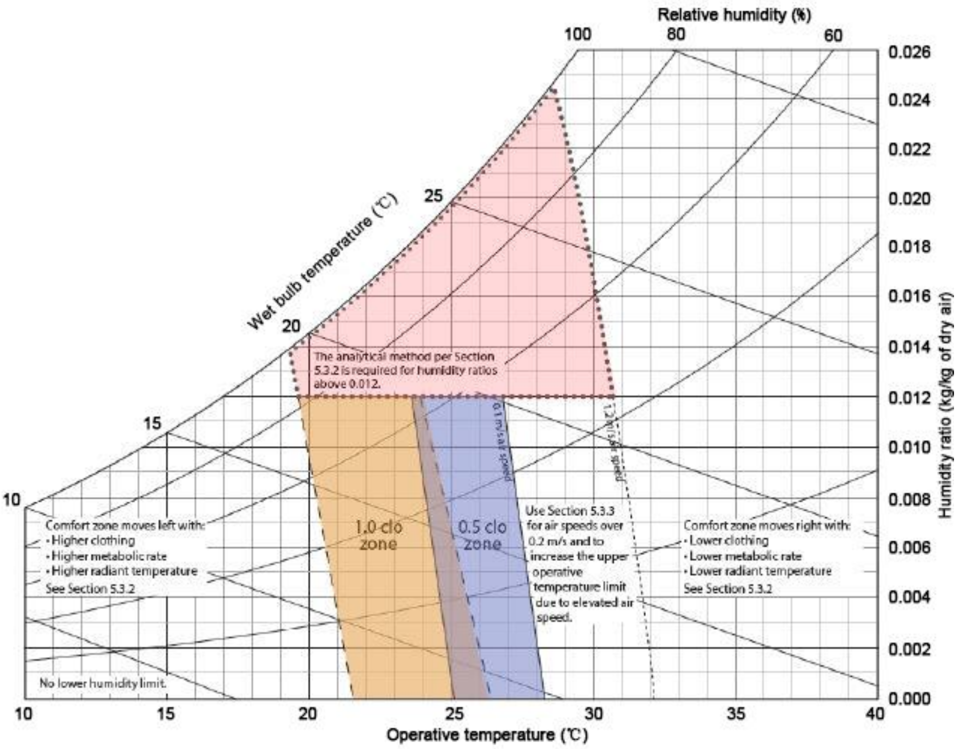


Fig. 1-9. Recommended comfort zone in ASHRAE-55 [7].

In addition, other standards were also conducted classification of thermal environment on the basis of PMV index, from which the higher required level, the narrower PMV interval, as shown in Table 1-3. For example, ISO 7730 suggested that the level A was corresponded to PMV in the range of -0.2 to 0.2 when occupants at the normal activity level (MR of 1.2met) with clothing insulation of 0.5clo in summer or 1.0clo in winter, such limitations were nearly close to the constant temperature state, and even controlled air speed within 0.2m/s [8].

Table 1-3. Classification of thermal environment in different standards [7, 8, 9, 27].

Standards	Category	PMV	PPD
ASHRAE-55 [7]	--	-0.5＜PMV＜0.5	＜10%
ISO 7730 [8]	A	-0.2＜PMV＜0.2	＜6%
	B	-0.5＜PMV＜0.5	＜10%
	C	-0.7＜PMV＜0.7	＜15%
EN 15251 [9]	I	-0.2＜PMV＜0.2	＜6%
	II	-0.5＜PMV＜0.5	＜10%
	III	-0.7＜PMV＜0.7	＜15%
	IV	PMV＜-0.7 or PMV＞0.7	＞15%
GB/T 50785 [27]	I	-0.5＜PMV＜0.5	＜10%
	II	-1＜PMV＜-0.5 or 0.5＜PMV＜1	10-25%
	III	PMV＜-1 or PMV＞1	＞25%

Except for PMV index, other scholars further proposed effective temperature (ET), new effective temperature (ET*) and standard effective temperature (SET*) etc. to describe the influence of environmental parameters on human thermal sensation. From which the ET overestimated the influence of humidity on comfort state at low temperature, although the ET* improved it and introduced the concept of skin moisture, it was only applicable to the conditions of lower air velocity and activity level. In addition, the consideration for skin temperature and moisture were also necessary in the calculation process of SET* and may result the application was limited to a certain extent.

Generally speaking, the static thermal comfort research based on artificial climate chamber experiment in early stage helped us to understand the relationship between human beings and the environment. PVM model provided a method for predicting the thermal comfort in a target environment and became an effective tool for determining indoor environmental parameters in air-conditioned buildings. However, accompanied by the popularity of HVAC, some health issues caused by which had begun to attract the attention of researchers, and the decrease of tolerance caused by stable environment was also the main reason for sick building syndrome (SBS).

1.2.3 Dynamic theory of adaptive thermal comfort

With the in-depth development of thermal comfort, field investigation that based on the actual environment had gradually become the main way for scholars to carry out the research. Compared with the method of artificial climate chamber, the field study could truly reflect the various psychological and physiological responses of occupants in actual built environment, which could provide more powerful evidence to further reveal the relationship between people and environment.

During the numerous field surveys, there was a common finding showed that, in the deviation from thermal neutral state (or non-air conditioned buildings), occupants showed a stronger ability to adapt to surrounding environment, and the actual thermal sensation (TSV) may varied from the predicted results by PMV, as shown in Fig.1-4. Thus, the viewpoint of thermal adaptability that based on the dynamic theory had been gradually formed in recent years.

The theory of adaptive thermal comfort revealed that human beings were not passive receivers of the target environment. In fact, there should be a complex interactive relationship between human and environment (give and take), in which they were the active participants [28]. It was is not the end of the thermal response if the occupants were not satisfied with current thermal environment, but the beginning of the adaptive process. Through multiple feedback loops with the environment, the influence of discomfort factors could be reduced as far as possible to achieve thermal comfort. The selective adaption in long-term process were mainly lie upon three aspects as following, Table 1-4:

Table 1-4. Basic mode of human thermal adaption.

Category	Sub-classification	Performance
① Behavioral adaption	•Personal adjustment	Change clothing and activity level, drink ice beverage etc.
	•Technical regulation	Open/close window, fans and HVAC etc.
	•Cultural adjustment	Napping, develop activities etc.
② Physiological adaption	•Genetic adaption	Racial heredity throughout life cycle.
	•Heat acclimatization	Transient physiological adaption to external stimuli.
③ Psychological adaption	--	Coupling reflection of thermal preference and long-term experience.

One thing need to point out that, the three ways mentioned above were not exist in isolation or acted independently, people's subjective response and evaluation to the environment were the coupling results of the three. The normal process of the thermal perception was following “physical stimulus - physiological response - thermal perception”, under the static conditions, physical stimulus and thermal response were matched with each other, and the results were either comfortable or uncomfortable (Fig.1-10, orange area). In actual indoor environment, the above procedures were still followed when occupants felt comfortable. Otherwise, multiple interactions with the environment would occurred through physiological and psychological feedback to achieve thermal comfort. In other words, discomfort was the driving force of the thermal adaptability, with the specific feedback loops as shown in Fig.1-10.

1) Physiological adaptive feedback

Compared with the static heat balance model that considered discomfort as the feedback result, adaptive thermal comfort theory put the discomfort as a starting point for feedback. When occupants were not satisfied with current environment, both physiological and behavior adjustment would play significant role on the process, such as change clothing, activity levels and open/close windows etc. Under the action of that long-term cycle effect, people could obtain the adaptability to the environment variation to some extent.

2) Psychological adaptive feedback

Occupants would psychologically establish a comfortable standard cognition of the current environment based on their long-term thermal experience and preference for the future. And it was easier to achieve comfort and satisfaction when subjective perception results tend to be the expectation.

In the feedback system mentioned above, the various adjustments would be affected by both outdoor climate and indoor microclimate, from which the microclimate was mainly determined by building envelope design and indoor working conditions.

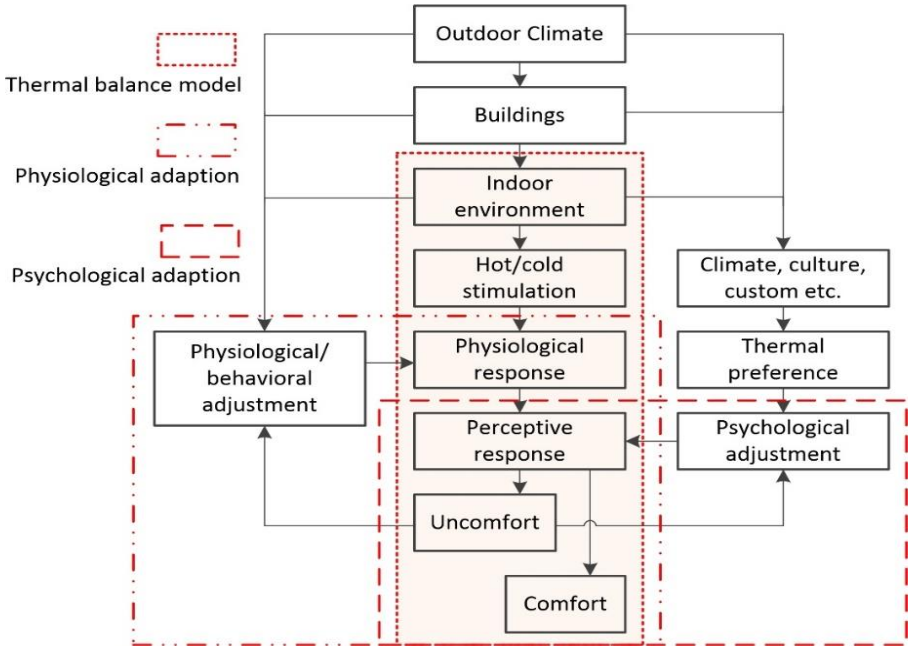


Fig. 1-10. The influence mechanism of thermal adaptability.

1.3 Research questions

The research questions of current thesis could be classified as following:

- How to achieve the unity of comfort and energy saving to the greatest extent according to different climatic conditions in China?
- What is the real indoor thermal environment of different working conditions for public buildings aiming at specific climatic characteristics?
- What are the occupants' differences in adaptation to different physical environments?
- How to define the quantitative relationship of different regulatory mechanisms for human different adaptive capacities?
- How to guide the revision of energy efficiency standards by quantifying the comfort level?

1.4 Purpose of the research

With issues mentioned above, the purpose of this thesis mainly lie upon five points as following:

- To probe authentic indoor physical environment and actual thermal comfort for different climate zones in China.
- To determine occupants' neutral (comfort) temperature, preference temperature and acceptable temperature range in different working conditioned buildings.
- To explore the human's adaptive regulatory mechanisms in different working conditioned public buildings.
- To establish the adaptive model of human sensation that in consideration of the specific climatic conditions.
- To verify the accuracy of recommended models in ASHRAE-55, EN 15251 and Chinese GB/T 50785 comparing to actual working conditions.

1.5 Research content and framework

The research content of current thesis are listed below, with the research framework is shown in Fig.1-11.

In chapter 1, the background was firstly elaborated. In addition, the development status of thermal comfort were reviewed. And then proposed the target of the research based on the questions raised.

In chapter 2, the two main research ideals (adjustment PMV model and adaptive comfort model) of the adaptive approach were presented. And focused on the adaptive model, three aspects namely field investigation, climatic adaptability and application were reviewed, respectively.

In chapter 3, the research methodology was expounded. Firstly, two approaches for climate classifications were introduced. In addition, the establishment of adjustment PMV model and adaptive model were explained. Lastly, combined with the evaluation indexes extracted, the whole research process was described in detail.

In chapter 4, based on adaptive comfort model approach, a systematic investigation was conducted for public building standard rooms with evaporative cooling air conditioned system (ECS) in Urumqi (China). Meanwhile, the authentic indoor physical environment and actual thermal comfort were surveyed. Through the regression analysis, the neutral (comfort) temperature, preference temperature and acceptable temperature range in ECS buildings were determined, respectively. Ultimately, the adaptive model was established by using the relationship between outdoor prevailing mean temperature and indoor comfort temperature.

In chapter 5, based on adaptive comfort model approach, a pilot study was further unfolded for different indoor operation modes between evaporative cooling air conditioned and naturally ventilated buildings in Turpan (China). The differences of selective behavior adjustment were concluded. Meanwhile, verified the accuracy of recommended models in ASHRAE-55, EN 15251 and Chinese GB/T 50785 comparing to each working conditions.

In chapter 6, based on adjustment PMV model approach, the optimization of various parameters for Chinese climate zones were carried out with consideration of energy demands and adaptive thermal comfort by simulation study. To be specific, five typical benchmark cases with climatic adaptability were established. At the same time, with the help of numerical calculation, a further coupling calculation of indoor adaptive thermal comfort was conducted to search for the best thermal range with less energy consumption.

In chapter 7, the conclusions of the whole thesis was summarized and the future work of adaptive thermal comfort had been discussed.

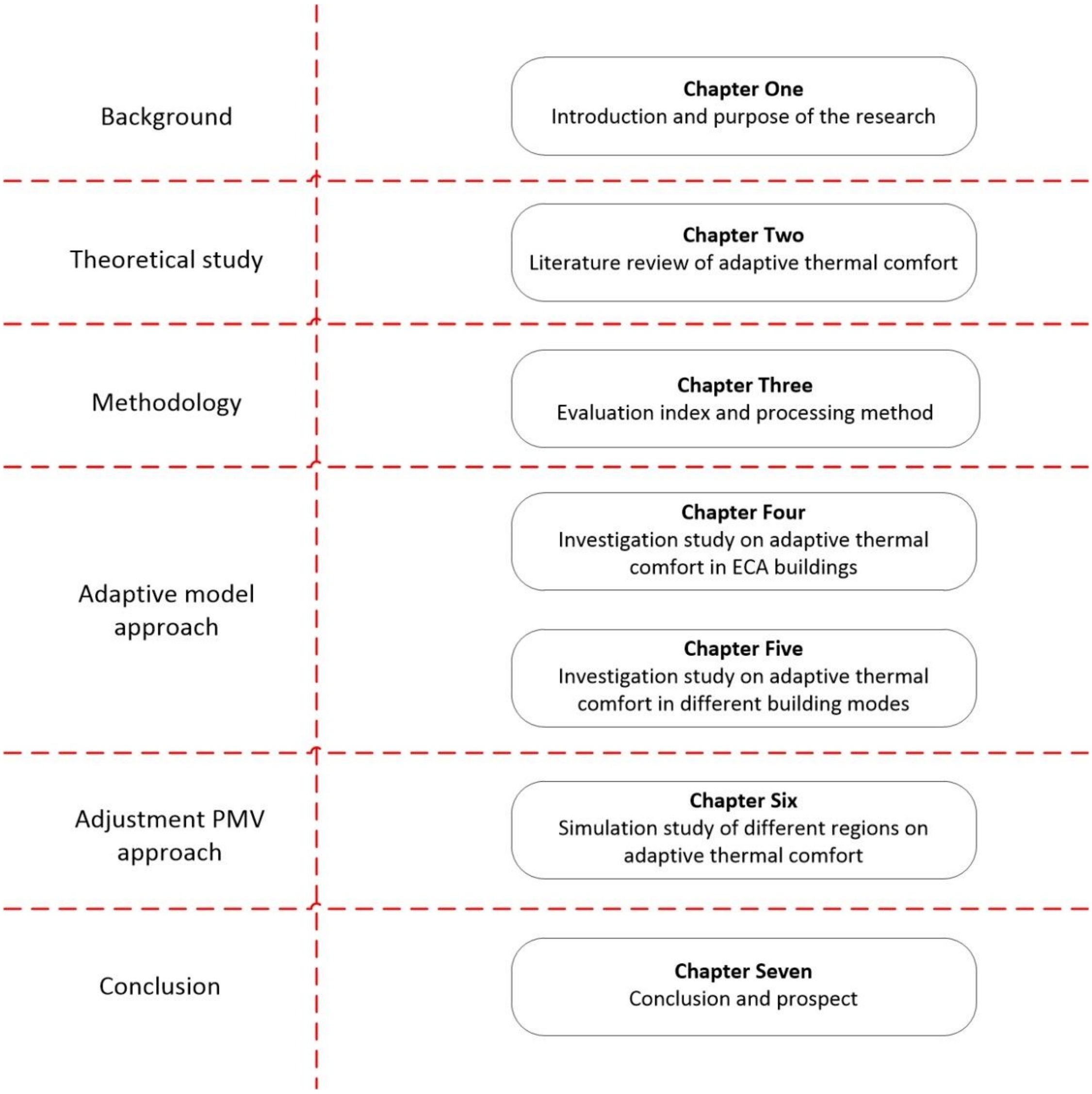


Fig. 1-11. Research framework.

Reference

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Chapter 2

LITERATURE REVIEW

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2.1 Research ideas of adaptive thermal comfort

In order to cope with the issue of oil crisis, the adaptive theory of thermal comfort was firstly taken into account since 1970s. Numerous scholars believed that the deviation between PMV and TSV mainly due to the input error of the model. Moreover, the static environment that based on the artificial climate laboratory ignored the human-environmental interaction (thermal adaptability). Therefore, this chapter mainly focus on the dynamic adaptive approach to carry out a short review. Generally speaking, the dominating research ideas of adaptive thermal comfort were including two aspects, namely adjustment PMV model and adaptive comfort model, respectively.

2.1.1 Adjustment PMV model

1) Fanger and Toftum's expectancy factor "e"

In terms of naturally ventilated buildings, multiple studies reported the rational comfort model (PMV) underestimated the thermal sensation of occupants while others reported an overestimation [1]. Fanger and Toftum [2] recognized the differences in the thermal expectation, behavioral variation and physiological adaption factors in long-term living in different climate zones and proposed expectancy factor "e" to correct the calculated PMV. To be specific, it was multiplied by a corresponding thermal expectative factor based on the value of PMV, as shown in Eq.2-1.

$$PMV_e = e \times PMV \qquad (2\text{-}1)$$

Where the two essential conditions of expectancy factor (e, 0.5 - 1) were duration time period of the hot climate and the comparison between local air-conditioned and non-air conditioned buildings, the estimated value were listed in Table 2-1.

Table 2-1. Expectancy factor "e" in naturally ventilated buildings [3].

Level	Building classification	e-value
Low	Naturally ventilated buildings are located in areas where with few air-conditioned buildings and hot climate throughout all seasons.	0.5-0.7
Medium	Naturally ventilated buildings are located in areas where with some air-conditioned buildings and it is hot in summer.	0.7-0.9
High	Naturally ventilated buildings are located in areas where with many air-conditioned buildings and hot period occur briefly in summer.	0.9-1.0

Afterwards, other researchers conducted studies in Thailand, Singapore, Greece, Australia, China etc., and proposed different expectancy factor values for non-air conditioned buildings, as shown in Table 2-2. In which the thermal preference was considered to be an appropriate element to explain the overestimation of thermal sensation in non-air conditioned buildings by PMV model and had been partially verified.

Table 2-2. Expectancy factor “e” in different countries [3-7].

Country	City	e-value	Reference
Thailand	Bangkok	0.6	[3]
Singapore	Singapore	0.7	[4]
Greek	Athens	0.7	[3]
Australia	Brisbane	0.9	[3]
China	Shanghai	0.64	[5]
China	Changsha	0.8	[6]
China	Guangzhou	0.7	[7]

2) R. Yao's adaptive coefficient “ λ ”

Although the expectancy factor revised the Fanger’s rational thermal comfort model, it only considered the psychological influence and ignored the physiological adaptation of humans to the thermal environment. R. Yao [8] developed adaptive predicted mean vote (APMV) by using the “black-box” theory under free-running conditions and proposed adaptive coefficient “ λ ” , which considered multiple factors such as culture, climate, society, psychological and behavior adaption. The equation could be obtained by adopting the least square method and described as Eq.2-2.

$$APMV = PMV/(1 + \lambda PMV) \qquad (2\text{-}2)$$

The values of adaptive coefficient “ λ ” reflected occupants adaptive functions such as behavior and psychological adaptation. When λ was zero, the APMV was equal to PMV, which is the lab-based condition with no adaptive action. In warm conditions, as the PMV was greater than zero, the APMV would be less than PMV; in cool conditions, as the PMV was less than zero, the APMV would be greater than PMV. It means that in warm conditions, the occupant’s thermal comfort sensation in a certain environment condition could feel less hot than the PMV index predicted. Vice versa, in cool conditions, the thermal comfort sensation in a certain environment condition could be less cold than the PMV index predicted. The specific adaptive diagram is shown in Fig.2-1. It was worthwhile mentioning that the APMV model would also be useful to the study of dynamic thermal comfort temperature set-points, which was one of the key factors affecting building energy consumption.

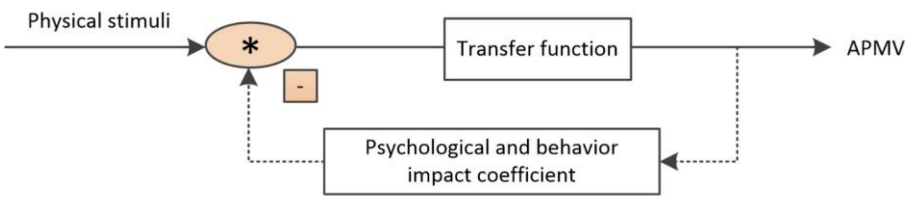

Fig. 2-1. Thermal comfort adaptive model diagram [8].

3) Tsinghua University's adjustment model

The research team of Tsinghua University (R. Zhao, Y. Zhu and X. Zhou, et al.) pointed out that, in non-air conditioned buildings, the power spectral density and turbulence intensity of airflow were also play a significant role on thermal sensation. In other words, the dynamic characteristics of the airflow could effectively improve the discomfort of human body in the hot environment, so as to achieve a higher neutral temperature [9].

The body's perception of dynamic airflow was thought to be related to thermal adaption. X. Zhou [10] indicted that, as the environment deviated from neutral conditions, both outdoor daily mean air temperature ($T_{out,d}$), indoor operative temperature (T_o) and mean air velocity (V_o) would affect the deviation between predicted and actual mean votes, that namely $\triangle PMV$. According to the results of multiple linear regression could obtained mathematical model as Eq.2-3.

$$PMV^* = PMV - \triangle PMV$$

$$\triangle PMV = 6.961 - 0.26\times T_o - 0.262\times T_{out,d} - 5.104\times V_o + 0.01\times T_o\times T_{out,d} + 0.21\times T_o\times V_o \quad (2\text{-}3)$$

where $\triangle PMV$ is adjustment PMV, T_o is indoor operative temperature (℃), $T_{out,d}$ is outdoor daily mean air temperature (℃) and V_o is indoor air velocity (m/s). When the outdoor daily mean air temperature was between 10℃ and 32℃, indoor operative temperature in the range of 26℃ to 32℃ and mean air velocity within 1.4m/s, the model in Eq.2-3 could be applied. Meanwhile, the adjustment PMV model (PMV*) could reflect the influence of various environmental parameters on thermal sensation in a relatively hot conditions.

2.1.2 Adaptive comfort model

By collected field survey results and compared with the index of heat balance model, Humphreys and Nicol firstly proposed the concept of adaptive comfort model to explain the deviation between actual sensation and predicted results [11,12]. Adaptive comfort model showed a strong linear relationship between human neutral temperature and outdoor climate conditions, with the principle was that if a state of discomfort arises, occupants would respond to maintain their comfort. From which the response was refereed adaptability, including physiological, psychological, social, technical, cultural and behavioral adaptive reactions. In an environment with fewer constraints, adaptability would play a powerful role that leading the neutral temperature was close to the actual conditions; vice versa, a more restrictive environment could resulting a deviation between them. In this adaptive hypothesis, human being was no longer a passive recipient of the environment, but in a dynamic balance of active interaction with the current environment [13]. Occupants with surrounding environment was regarded as a dynamic system in which comfort and discomfort had dynamic characteristics with time variation.

Brager and de Dear further developed the theory of adaptive comfort model, and systemically put forward the built environment - human body adaptive model. In which the feedback was regarded as an important feature of the adaptation mechanism and divided into three modes, namely behavior adjustment, physiological acclimatization and psychological adaption [14]. According to the conceptual description, occupants' perceived discomfort could be mitigated to some extent through the feedback loop of the three ways mentioned above. Specifically speaking, the feedback of behavior adjustment was reflected in PMV models through the changes in parameters such as air velocity and clothing insulation, while the feedback of psychological adaption was considered as the most likely explanation for the deviations in PMV models in naturally ventilated buildings. Brager and de Dear described the psychological adaption mechanism with the preference as the core content, and believed it was a change in perception caused by thermal experience and expectation.

As afore-mentioned, the significance of the proposed adaptive comfort model were lie upon three points as follows:

- The research method of the thermal comfort was expanded, which was transformed from a single laboratory study to a combination of laboratory study and field investigation.
- A new research idea was proposed. PMV model was used to predict the human thermal sensation under a given combination of environmental parameters, while the adaptive approach predicted in what kind of environment would be comfortable.
- The adaptive model considered the adaptability of human to climate, by expanding the acceptable temperature range could achieve the purpose of energy saving.

2.2 Review of adaptive comfort model based on field investigation

2.2.1 Establishment of thermal comfort database

1) Early database of Humphreys

During the period of 1930 to 1975, Humphreys conducted more than 30 field investigations and obtained approximately 200000 comfort research samples, which including the occupants from Asia, Europe, Africa, America and Australia. The measurement indicators contained air temperature, relative humidity, air velocity and mean radiant temperature, meanwhile, the seven-point scale (-3 to 3) was adopted to describe the human thermal sensation. A predictive model was proposed by analyzing the effects of indoor and outdoor transition on thermal comfort, the quantitative relationship between thermal comfort and climate was explored for the first time [11,15].

2) SCATs database (EN 15251)

From 1996 to 2000, Humphreys and Nicol carried out the project of SCATs (Smart Controls and Thermal Comfort) in Europe (France, Greece, Portugal, Sweden and United Kingdom) to explore the thermal comfort research, the purpose of which was to reduce the energy consumption of the air conditioned system through the use of adaptive method [16]. Totally of 26 buildings with around 31939 raw data were achieved during the field survey which including the naturally ventilated (NV), air conditioned (AC) and mixed mode (MM) buildings. The environmental parameters were recorded by using the mobile automatic data collection system, and each response sample was attached with air temperature, black bulb temperature, air velocity and relative humidity, etc. Moreover, subjective questionnaires were including air temperature/relative humidity/air velocity's sensation vote (seven-scale point) and preference vote (five-scale point) [17]. By adopting the Griffiths constant method to determine the occupants' neutral temperature, so as to obtained the control algorithm of the European adaptive model.

3) RP-884 database (ASHRAE-55)

In 1998, Brager and de Dear based on the program of RP-884, collected the 160 buildings with approximately 21000 sets of data from four continents (mainly in America and Australia) during field investigation [18]. Except for the air temperature, relative humidity, air velocity and mean radiant temperature, the clothing insulation and metabolic rate were also taken into account seriously. Some surveys had even measured radiation asymmetry and air turbulence with different height. Generally speaking, the operative temperature was adopted as the indoor environmental evaluation index, and the neutral temperature was calculated by weighted regression. Meanwhile, the mean monthly temperature was chosen as outdoor assessment criteria and established the adaptive model between indoor neutral temperature and outdoor climate in naturally ventilated buildings.

4) Other database

Due to the reality of the actual buildings and the interaction between human and the environment were taken into consideration, the field investigation had become a significant part of thermal comfort research. Except for the three large-scale integrated studies mentioned above, other field surveys had also been carried out around the world in recent years. The specific global pilot distribution of field investigation is shown in Fig.2-2 (orange dots). It can be observed that, the field studies of thermal comfort abroad covered a wide range of climate types around the world, which including around 300 buildings such as office, residences and classrooms etc.

However, the development of adaptive thermal comfort was relatively late in China, which was only attracted attention by domestic scholars after the adaptive theory was put forward. In 1993, F. Tan [19] firstly conducted field survey for office buildings in severe cold zone of China during winter season; five years later, Y. Xia [20] conducted physical measurements and questionnaires on thermal comfort in 88 naturally ventilated residential buildings in Beijing. Afterwards, a series of field investigation had been carried out in China, from which including the majority of eastern areas such as temperate, subtropical and tropical zone, as shown in Fig.2-3. Nevertheless, for most of the western region of China as well as the western typical temperate continental climate area, the samples based on field investigation were still necessary to be established.

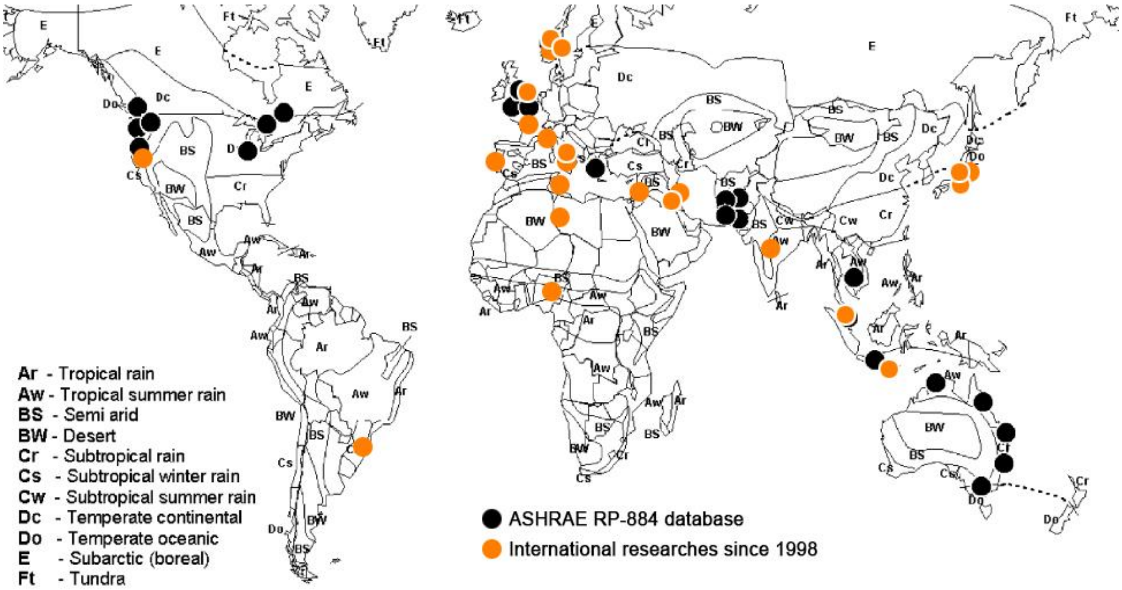

Fig. 2-2. The global pilot distribution of field investigation.

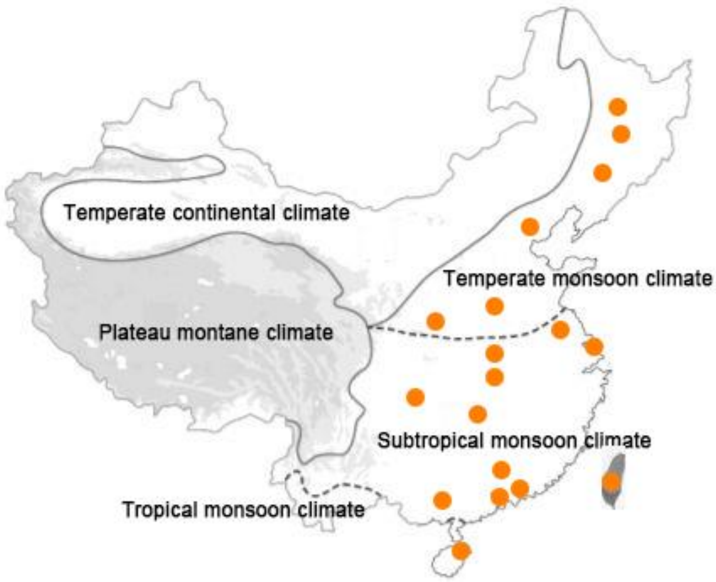

Fig. 2-3. The pilot distribution of field investigation in China.

2.2.2 Establishment of adaptive comfort model

1) Research on adaptive model in foreign countries

Based on the establishment of the field investigation database, multiple researchers attempted to link the indoor comfortable temperature with outdoor climate so as to establish the adaptive models that suitable for various countries and climate regions. It considered that the comfort temperature or acceptable temperature range would be change with the outdoor monthly mean temperature's variation. Up to now, the international famous adaptive models were represented by Humphreys & Nicol and Brager & de Dear, respectively.

Humphreys and Nicol [21,22] based on the data obtained from different background factors in 36 regions, and deduced adaptive comfort model of universal significance, as shown in Eq.2-4. From which T_n is neutral temperature (℃) and T_{a,out_av} is outdoor monthly mean temperature (℃).

$$T_n = 0.33 \times T_{a,out\_av} + 18.8 \qquad (2\text{-}4)$$

Brager and de Dear [23] established the adaptive comfort model in naturally ventilated buildings through the systematic arrangement and analysis of RP-884 project, as listed in Eq.2-5. From which T_{comf} is indoor comfort temperature (°C) and T_{a,out_av} is outdoor monthly mean temperature (°C). On that basis, the indoor comfortable temperature interval was defined according to 80% and 90% acceptability, and the corresponding TSV value was equal to ±0.85 and ±0.5, respectively, so as to determine the acceptable range of indoor effective temperature in naturally ventilated buildings.

$$T_{comf} = 0.31 \times T_{a,out\_av} + 17.8 \qquad (2\text{-}5)$$

Due to the differences with culture, geography, climate and technology in various countries, which may lead the adaptive comfort models varying from each other. Table 2-3 summarized part of the research results by foreign scholars according to the time node.

Table 2-3. Summary of foreign adaptive comfort models.

Researcher	Time	Location	Adaptive model	Sample
Humphreys [11]	＜1976	Africa, America, Asia, Europe, Australia	$T_n = 0.534T_{a,out\_av} + 13.5$	200000
Auliciems [24]	1986	Australia	$T_{comf} = 0.31T_{a,out\_av} + 17.6$	1800
Nicol [25]	1993-1994	Pakistan (short term)	$T_n = 0.38T_{a,out\_av} + 17.0$	4927
Nicol [26]	1995-1996	Pakistan (long term)	$T_n = 0.36T_{a,out\_av} + 18.5$	7112
ASHRAE-55 [27]	1997-1998	Indonesia, Pakistan, Singapore, Thailand, UK, USA	$T_{comf} = 0.31T_{a,out\_av} + 17.8$	21000

Heidari [28]	1998	Iran (short term)	$T_n=0.36T_{a,out\_av}+17.3$	891
Heidari [28]	1999	Iran (long term)	$T_n=0.292T_{a,out\_av}+18.1$	3819
EN 15251 [29]	2002	France, UK, Greece, Portugal, Sweden	$T_n=0.33T_{a,out\_av}+18.8$	31939
Bouden [30]	2005	Tunisia	$T_{comf}=0.68T_{a,out\_av}+6.88$	2400
Ricciardi [31]	2011	Italy	$T_n=0.15T_{a,out\_av}+19.35$	588
Martin [32]	2015-2016	Spain	$T_n=0.243T_{a,out\_av}+19.284$	5134
Singh [33]	2016	India	$T_n=0.36T_{a,out\_av}+16.94$	460
Rupp [34]	2016-2017	Brazil	$T_n=0.56T_{a,out\_av}+12.74$	5500
Indraganti [35]	2017	Qatar	$T_n=0.049T_{a,out\_av}+22.5$	3742
Thapa [36]	2017	India	$T_n=0.64T_{a,out\_av}+9.02$	--
López-Pérez [37]	2018	Mexico	$T_n=0.13T_{a,out\_av}+22.7$	496
Tewari [38]	2019	India	$T_{comf}=0.22T_{a,out\_av}+21.5$	1554
Rijal [39]	2019	Japan	$T_n=0.065T_{a,out\_av}+23.9$	36114

Note: T_n is neutral temperature (°C), T_{a,out_av} is outdoor monthly mean temperature (°C) and T_{comf} is indoor comfort temperature (°C).

2) Research on adaptive model in China

Due to China's vast territory and diverse climatic conditions, the living habits, economic level and the economic bearing capacity were variating from each other. Hence, whether the differences were existed in occupants' adaptability to the thermal environment in various climate regions? With these questions, L. Yang [40] firstly conducted field investigations on residential buildings in five representative cities (Harbin, Beijing, Xi'an, Shanghai and Guangzhou) in 2003, and achieved the Chinese adaptive comfort models with the same research method that used by foreign researchers. From then on, Chinese scholars began to carry out the field investigation and research on thermal comfort in severe cold zone (SCZ), cold zone (CZ), hot summer and cold winter zone (HSCW), hot summer and warm winter zone (HSWW) and mild zone (MZ), respectively. Table 2-4 presented the adaptive models by Chinese scholars according to the time node.

Table 2-4. Summary of Chinese adaptive comfort models.

Researcher	Time	Location	Adaptive model	Sample
L. Yang [40]	2001-2003	Harbin, Beijing, Xi'an, Shanghai, Guangzhou	$T_n=0.30T_{a,out\_av}+17.9$	--
Mui [41]	2003	Hong Kong	$T_n=0.16T_{a,out\_av}+18.3$	55
X. Ye [42]	2003-2004	Shanghai	$T_n=0.42T_{a,out\_av}+15.1$	1768

Y. Mao [43]	2005	Harbin, Changchun, Shenyang	$T_n = 0.12T_{a,out\_av} + 21.5$	30
	2005	Beijing, Zhengzhou, Xi'an	$T_n = 0.27T_{a,out\_av} + 20.0$	30
	2005	Nanjing, Chongqing, Shanghai	$T_n = 0.33T_{a,out\_av} + 16.9$	30
	2005	Nanning, Guangzhou, Haikou	$T_n = 0.55T_{a,out\_av} + 10.6$	30
X. Guo [44]	2005	Harbin	$T_n = 0.28T_{a,out\_av} + 20.4$	135
J. Liu [45]	2005-2006	Chongqing	$T_n = 0.23T_{a,out\_av} + 16.9$	3621
W. Yang [46]	2006	Changsha	$T_n = 0.25T_{a,out\_av} + 16.6$	--
W. Yang [47]	2006	Changsha, Wuhan, Jiujiang, Nanjing, Shanghai	$T_n = 0.32T_{a,out\_av} + 17.5$	129
J. Li [48]	2006-2007	Nanyang	$T_n = 0.61T_{a,out\_av} + 14.7$	1596
J. Han [49]	2006-2007	Changsha	$T_n = 0.67T_{a,out\_av} + 10.3$	101
	2006-2007	Yueyang	$T_n = 0.44T_{a,out\_av} + 9.2$	131
H. Mao [50]	2009	Chengdu	$T_n = 0.73T_{a,out\_av} + 9.0$	1737
Z. Jin [51]	2011	Chongqing, Wuhan, Fuzhou, Kunming	$T_n = 0.51T_{a,out\_av} + 10.4$ $T_n = 0.22T_{a,out\_av} + 20.3$ $T_n = 0.42T_{a,out\_av} + 14.0$ $T_n = 0.6T_{a,out\_av} + 11.03$	18513
H. Yan [52]	2013	Turpan, Baotou, Yinchuan, Jiaozuo, Weinan, Hanzhong, Kunming, Lhasa	South: $T_n = 0.48T_{a,out\_av} + 13.8$ North: $T_n = 0.007T_{a,out\_av}^2 + 0.083T_{a,out\_av} + 19.94$	--
Y. Jiao [53]	2014-2017	Shanghai	$T_n = 0.4T_{a,out\_av} + 16.0$	1040
Z. Wu [54]	2016	Changsha (NV)	$T_n = 0.19T_{a,out\_av} + 22.6$	467
Z. Wu [55]	2016	Changsha (AC)	$T_n = 0.01T_{a,out\_av} + 26.9$	442
Zheng [56]	2017	Xi'an	$T_n = 0.41T_{a,out\_av} + 15.4$	2069
C. Fu [57]	2018	Guangzhou	$T_n = 0.18T_{a,out\_av} + 22.9$	1179

Note: T_n is neutral temperature (℃), T_{a,out_av} is outdoor monthly mean temperature (℃), NV is naturally ventilated buildings and AC is air-conditioned buildings.

The establishment of the adaptive comfort model provided a reference for the design of indoor thermal environment: that is, in the early stage of design, the indoor neutral temperature obtained by simulation software could be compared with the value that calculated by adaptive model, so as to determine whether the natural ventilation could reach the comfortable state. Moreover, the value of adopting adaptive model for temperature setting may provide occupants with more freedom (i.e.

flexible working hours and clothing adjustments) to adapt to the indoor environment. However, adaptive models only attributed the indoor comfortable temperature to the influence of outdoor climatic conditions, which ignored many factors and was difficult to explain in mechanism. In fact, the indoor comfortable temperature was closely related to outdoor climate was mainly due to occupants tended to adjust their clothes to adapt to the climate variation, or there may form the seasonal physiological and psychological adaption within human beings, unfortunately, these factors have not been reflected in the model. In addition, by comparing with the Table 2-3 and Table 2-4 could observed that, the difference of indoor comfortable temperature with outdoor average temperature also varied from different countries and climate zones. With the rapid improvement of residents' living standards, whether the existing models could still be used to guide the design of future buildings remains to be discussed.

2.3 Review of thermal adaptability affected by climates

Climate played an important role on shaping the human thermal adaptability. For example, there were significant differences in human constitution, structure, skin color, physical appearance and other characteristics between cold regions with high latitude and hot regions with low latitude [58]. These differences may lead thermal adaptability varied from each other, from which the two important influencing factors were regionalism and seasonality, respectively.

2.3.1 Regionalism

Based on Köppen-Geiger classification, the global climate was divided into five categories: tropical moist climate, dry climate, moist subtropical mid-latitude climate, moist continental mid-latitude climate and polar climate [59].

In tropical moist climate zone, it could be observed that the research results were similar during investigation among Australia [60], Brazil [61], Indonesia [62], Malaysia [63] and Singapore [64]. That is, for naturally ventilated buildings, the neutral temperature were both distributed between 26℃ and 29.5℃ with the acceptable temperature interval of 22℃ to 32.5℃. For air conditioned buildings, that two value range were 24℃ - 27℃ and 22℃ - 28℃, respectively.

In dry climate zone, multiple researchers found that the wider acceptable temperature range was existed under the NV buildings. A study in Pakistan [26] showed that the comfort zone was distributed between 21℃ and 31℃ (black bulb temperature). The research in Libya [65] and Tunisia [30] appeared the same results with the comfort temperature range of 16℃ - 26.5℃ due to the similar climate and culture background. In addition, the field survey in Egypt [66] revealed that although the neutral temperature was a litter higher than 24.5℃, the 80% acceptable temperature interval was approximately 19.7℃ - 29.3℃ that was close to the results in Pakistan.

In moist subtropical mid-latitude climate zone, from the field study in Portugal [67], Italy [68], Hong Kong [41], Taiwan [69], Guangzhou [7], Changsha [70], Chongqing [71] etc. could be discovered that the fluctuation range of neutral temperature in air-conditioned buildings was narrower than naturally ventilated buildings. For example, it was found that the neutral temperature of air-conditioned office buildings in Hong Kong was 23.7°C in summer and 21.2°C in winter, meanwhile, most of them were between 19.5°C and 25°C, while the interval in naturally ventilated buildings was approximately 14°C to 32°C that showed occupants with a more resilient to the surrounding environment.

In moist continental mid-latitude climate zone, such as Harbin [72,73] and Canada [74], the neutral temperature range was 20°C - 25°C with the acceptable interval of 16.5°C - 26.5°C. According to the study in Harbin, the neutral temperature in winter was about 1.1℃ lower than that 10 years ago, which mainly due to the rapid development of economy and technology in China, the reduction of people's clothing at home may decrease the neutral temperature to some extent. Therefore, it can be observed that the neutral temperature varied with the different region, from which with the lowest value in the cold climate zone and highest in the dry hot climate area.

2.3.2 Seasonality

The important characteristic of outdoor climate is the seasonal variation, in other words, different seasons may lead comfort deviation in the same indoor environment. A research in the artificial climate chamber [75] showed that under the same subjects, experimental procedures and working conditions, the responses of skin temperature and heart rate of human body varied significantly in winter and summer. B. Cao [76] conducted field investigations during 2007-2008 and showed that, under the same indoor operative temperature, occupants felt cooler in transition season and hotter in winter. The lower outdoor air temperature, the stronger thermal adaptability of the human body to the cold indoor environment. Moreover, the experiment by X. Zhou [9,10] revealed that the thermal sensation votes were not affected by the outdoor climate when the indoor air temperature was close to neutral temperature (26°C - 28°C), but the higher outdoor temperature, the greater heating tolerance. Likewise, R. Ming [77] focused on five seasonal period classification: i.e. latter spring (LS), early cooling period (EC), middle cooling period (MC), latter cooling period (LC) and early autumn (EA), and the results showed that for the same outdoor temperatures in different seasons, occupants’ clothing insulation varied, indicated that the occupants were more sensitive to environmental changes in EA than in LS, as well as in EC than in LC.

As afore-mentioned, both the regional and seasonal characteristics of the climate would affect the thermal adaptation of human body. Nevertheless, if the behavioral adjustment and psychological adaptation would be change in some specific region was still need to be paid attention by a large number of field experiments.

2.4 Review of adaptive comfort model application

Up to now, with improving the theory of adaptive thermal comfort and building the data platform, researchers have proposed adaptive models to guide the design of naturally ventilated buildings (free running mode). Meanwhile, it was adopted by several international standards, such as ASHRAE-55 (America) [27], EN 15251 (European Union) [29], Dutch adaptive Standard (Netherlands) [78] and GB/T 50785 (China) [79] etc.

2.4.1 ASHRAE-55 Standard

Faced with the impact of CO_2 emissions on global climate, American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) firstly announced to adopt the adaptive model in national thermal comfort standard, which was established by Brager and de Dear through long-term field investigations across the world, as shown in Fig.2-4.

In Fig.2-4, the upper and lower boundaries of the neutral temperature were 80% and 90% acceptable temperature interval that defined by thermal sensation votes, and the corresponding voting values were ±0.85 and ±0.5, respectively. In addition, the 80% and 90% acceptable temperature range were calculated to be ±3.5℃ and ±2.5℃ of neutral temperature, respectively. The specific using conditions were outdoor temperature ranged from 10℃ to 33.5℃, meanwhile, occupants could operate windows flexibility with the metabolic rate within 1.3met.

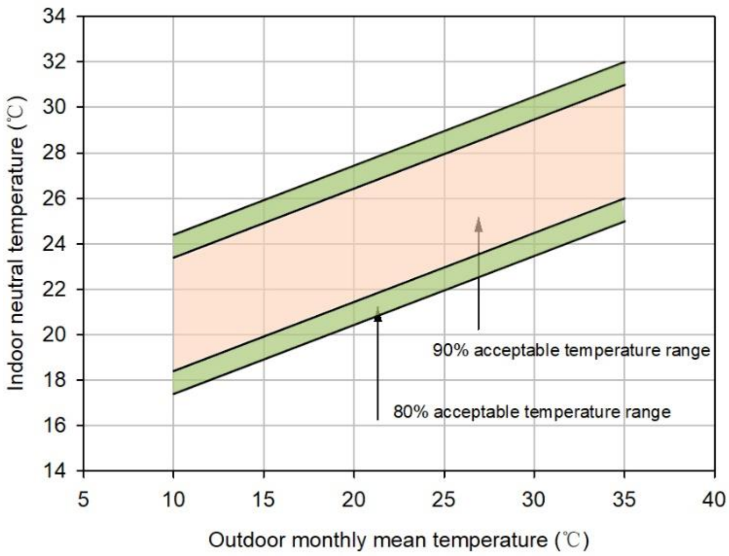

Fig. 2-4. Acceptable temperature range in naturally ventilated buildings in ASHRAE-55 [27].

2.4.2 EN 15251

At the background of SCATs program, an adaptive comfort algorithm was carried out to establish a variable indoor temperature standard, as listed in Eq.2-6.

$$T_{rm}=(T_{od-1}+0.8T_{od-2}+0.6T_{od-3}+0.5T_{od-4}+0.4T_{od-5}+0.3T_{od-6}+0.2T_{od-7})\ /\ 3.8 \qquad (2\text{-}6)$$

where T_{rm} is exponential weight continuous mean temperature (°C), T_{od-1} is the average daily outdoor temperature on the previous day (°C), T_{od-2} is the average daily outdoor temperature before 2 days (°C), etc. It is important to note that, the current day's mean outdoor temperature is not used in the equation, the primary reason is the highest temperature of current day is not obtained until 15:00 pm.

In Fig.2-5, three different comfort levels were defined according to the various building types, in which the specific prescribed indicators are summarized in Table 2-5. The related using conditions were only available in summer, and occupants could operate windows flexibility (no HVAC) with the metabolic rate within 1.3met.

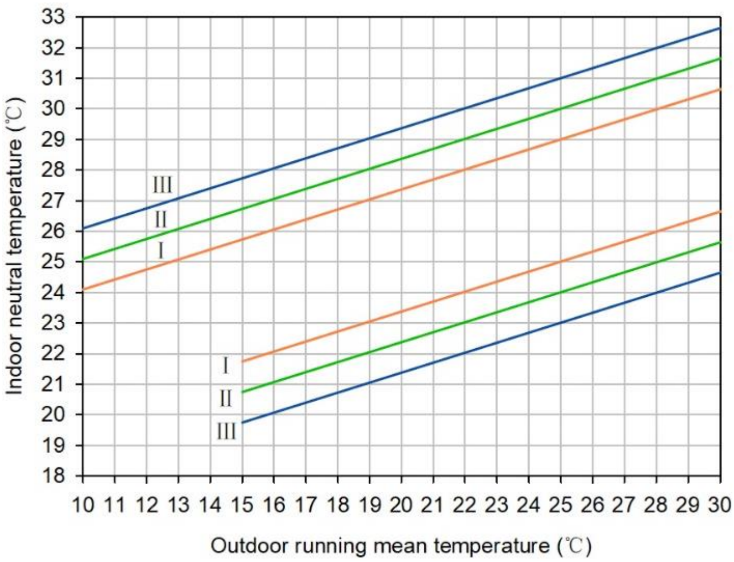

Fig. 2-5. Acceptable temperature range in free running buildings in EN 15251 [29].

Table 2-5. Classification of comfort levels in EN 15251 [29].

Level	Aimed buildings	Fluctuating range (compare with T_n)	PPD
I	Focus on sensitive and vulnerable users	±2°C	＜6%
II	New/modified/extended buildings	±3°C	＜10%
III	Existing buildings	±4°C	＜15%

2.4.3 Dutch adaptive Standard

According to the survey results by Brager and de Dear, a local standard that namely adaptive temperature limit (ATL) was established in Netherlands to evaluate indoor thermal environment [78]. And the mathematical model is expressed as Eq.2-7.

$$T_{rm}=(T_{od}+0.8T_{od-1}+0.4T_{od-2}+0.2T_{od-3})\ /\ 2.4 \qquad (2\text{-}7)$$

where T_{rm} is exponential weight continuous mean temperature (℃), T_{od} is the average daily outdoor temperature on current day (℃), T_{od-1} is the average daily outdoor temperature on the previous day (℃), etc.

Compared with ASHRAE-55 and EN 15251, the main feature of the Dutch Standard was the application of adaptive method to any type of the buildings. To be specific, the buildings were divided into two categories: α and β, meanwhile, different adaptive opportunities determine the ownership of that buildings. As for acceptable temperature interval, a new index of 60% was added on the basis of 80% and 90% limitation, as shown in Fig.2-6. In which level A (90%) represented the best indoor environment of the three and was suitable for the users with higher comfort requirements; level B (80%) was more practical for general office buildings; and level C (65%) was fit for other types of buildings, as shown in Table 2-6.

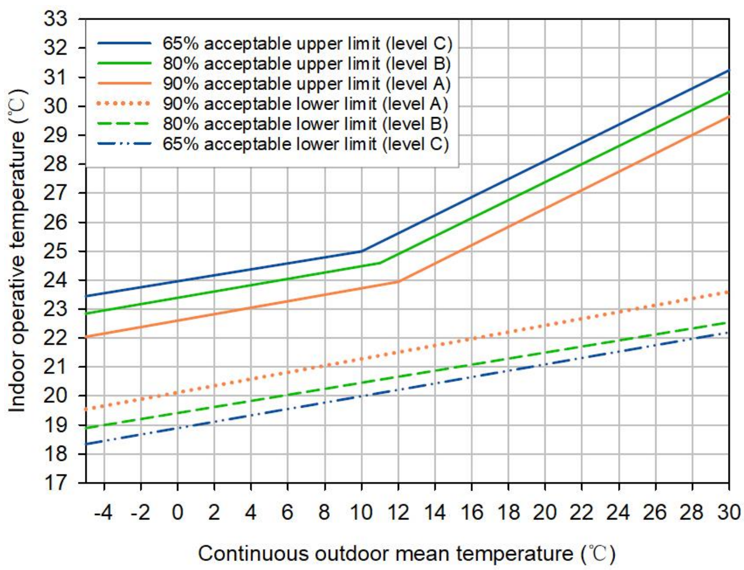

Fig. 2-6. Acceptable temperature range in α buildings based on ATL [78].

Table 2-6. Recommended upper comfortable temperature limit based on ATL [78].

Level	Description	Comfort temperature	Comfort temperature (α buildings, $T_{ext-ref}>12$℃)
A-90%	Very good	$T_n<0.11T_{ext-ref}+22.70$	$T_n<0.31T_{ext-ref}+20.30$
B-80%	Good	$T_n<0.11T_{ext-ref}+23.45$	$T_n<0.31T_{ext-ref}+21.30$
C-65%	Acceptable	$T_n<0.11T_{ext-ref}+23.95$	$T_n<0.31T_{ext-ref}+22.00$

Note: T_n is neutral temperature (℃), $T_{ext-ref}$ is outdoor reference temperature (℃) and α buildings referred that with more adaptive opportunities.

2.4.4 GB/T 50785

On the basis of field investigations for five climate zones in China, the first evaluation standard for indoor thermal environment in civil buildings was established by Chongqing University in 2012 (GB/T 50785-2012) [79], which considered the characteristics of regional climate variation and people's behavior and physiological regulation (i.e. thermal adaptability). Meanwhile, according to the classification, artificial and non-artificial cold/heat source thermal environment were carried out to be evaluated [80]. For non-artificial buildings (free running/naturally ventilated mode), there are mainly two methods as following.

1) Calculated method

When using the calculated method to judge the indoor environment, adaptive predicted mean vote (APMV) should be adopted as the evaluation basis, with the specific calculation procedure followed by Eq.2-2. In which the recommended values of adaptive coefficient "λ" were listed as Table 2-7 and the three different levels were shown in Table 2-8.

Table 2-7. Recommended value of adaptive coefficient "λ" [79].

Climate zone		Residences, hotels, offices, etc.	Educational buildings
SCZ, CZ	PMV≥0	0.24	0.21
	PMV<0	- 0.50	- 0.29
HSCW, HSWW, MZ	PMV≥0	0.21	0.17
	PMV<0	- 0.49	- 0.28

Note: SCZ is severe cold zone, CZ is cold zone, HSCW is hot summer and cold winter zone, HSWW is hot summer and warm winter zone and MZ is mild zone.

Table 2-8. Evaluation level of non-artificial cold/heat source thermal environment [79].

Level	Assessment criteria (APMV)
I	-0.5≤APMV≤0.5
II	-1≤APMV<-0.5 or 0.5<APMV≤1
III	APMV<-1 or APMV>1

Note: APMV is adaptive predicted mean vote (adjustment PMV model).

2) Graphic method

When adopting graphic method to judge the indoor environment, exponential weight continuous mean temperature (T_{rm}) was chosen to represent the outdoor climate condition. The specific mathematical algorithm is expressed as Eq.2-8.

$$T_{rm}=(1-\alpha)\ (T_{od-1}+\alpha T_{od-2}+\alpha^2 T_{od-3}+\alpha^3 T_{od-4}+\alpha^4 T_{od-5}+\alpha^5 T_{od-6}+\alpha^6 T_{od-7}) \qquad (2\text{-}8)$$

where T_{rm} is exponential weight continuous mean temperature (°C), α is the coefficient that ranges from 0 to 1, T_{od-n} is the mean outdoor temperature within N days (°C). And the related value limitation for different climate zones are shown in Table 2-9, 2-10 and Fig.2-7, 2-8.

Table 2-9. Evaluation level of non-artificial cold/heat source environment in SCZ and CZ [79].

Level	Assessment criteria	Limited scope
I	$T_{op\ I,\ b} \leq T_{op} \leq T_{op\ I,\ a}$ $T_{op\ I,\ a}=0.77T_{rm}+12.04$ $T_{op\ I,\ b}=0.87T_{rm}+2.76$	$18°C \leq T_{op} \leq 28°C$
II	$T_{op\ II,\ b} \leq T_{op} \leq T_{op\ II,\ a}$ $T_{op\ II,\ a}=0.73T_{rm}+15.28$ $T_{op\ II,\ b}=0.91T_{rm}-0.48$	$18°C \leq T_{op\ II,\ a} \leq 30°C$ $16°C \leq T_{op\ II,\ b} \leq 28°C$ $16°C \leq T_{op} \leq 30°C$
III	$T_{op} \leq T_{op\ II,\ b}$ or $T_{op\ II,\ a} \leq T_{op}$	$18°C \leq T_{op\ II,\ a} \leq 30°C$ $16°C \leq T_{op\ II,\ b} \leq 28°C$

Note: T_{op} is operative temperature (°C), T_{rm} is exponential weight continuous mean temperature (°C), SCZ is severe cold zone and CZ is cold zone. Level I and II area are shown in Fig.2-7.

Table 2-10. Evaluation level of non-artificial cold/heat source thermal environment in HSCW, HSWW and MZ [79].

Level	Assessment criteria	Limited scope
I	$T_{op\ I,\ b} \leq T_{op} \leq T_{op\ I,\ a}$ $T_{op\ I,\ a}=0.77T_{rm}+9.34$ $T_{op\ I,\ b}=0.87T_{rm}-0.31$	$18°C \leq T_{op} \leq 28°C$
II	$T_{op\ II,\ b} \leq T_{op} \leq T_{op\ II,\ a}$ $T_{op\ II,\ a}=0.73T_{rm}+12.72$ $T_{op\ II,\ b}=0.91T_{rm}-3.69$	$18°C \leq T_{op\ II,\ a} \leq 30°C$ $16°C \leq T_{op\ II,\ b} \leq 28°C$ $16°C \leq T_{op} \leq 30°C$
III	$T_{op} \leq T_{op\ II,\ b}$ or $T_{op\ II,\ a} \leq T_{op}$	$18°C \leq T_{op\ II,\ a} \leq 30°C$ $16°C \leq T_{op\ II,\ b} \leq 28°C$

Note: T_{op} is operative temperature (°C), T_{rm} is exponential weight continuous mean temperature (°C), HSCW is hot summer and cold winter zone, HSWW is hot summer and warm winter zone and MZ is mild zone. Level I and II area are shown in Fig.2-8.

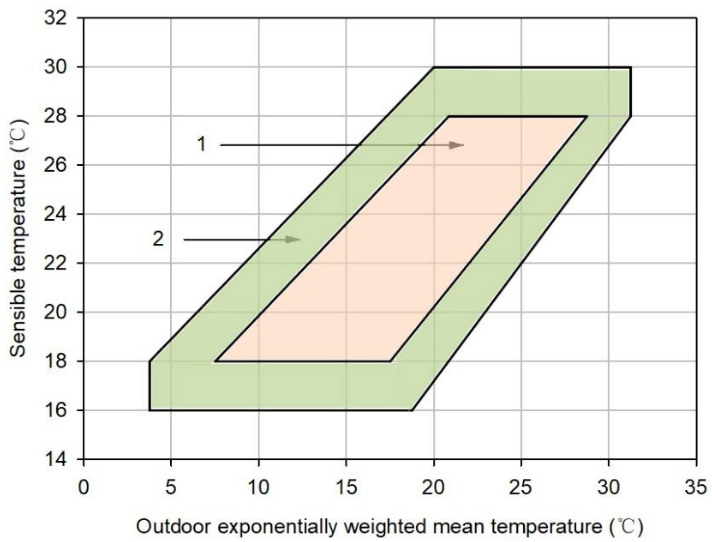

Fig. 2-7. Body sensing temperature range of non-artificial cold/heat source thermal environment. (SCZ and CZ) [79]

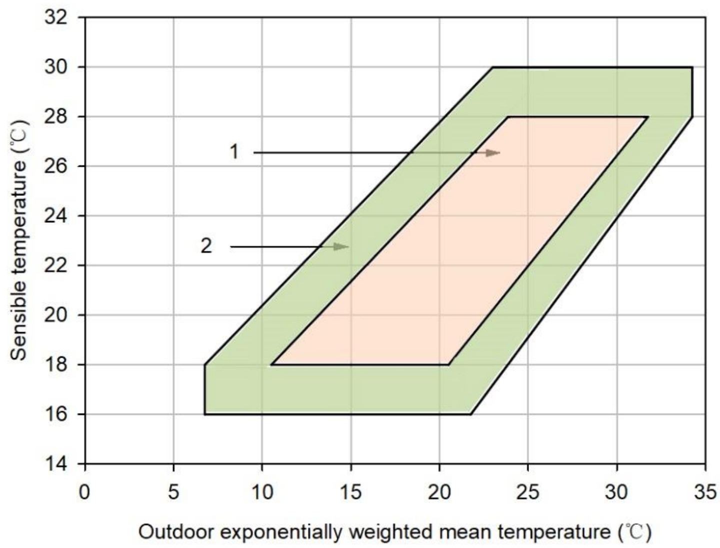

Fig. 2-8. Body sensing temperature range of non-artificial cold/heat source thermal environment. (HSCW, HSWW and MZ) [79]

Level I is the light orange area in the figure that corresponding to more than 90% satisfaction by occupants, and level II (light green) was represent for 75%-90% satisfaction. In the evaluation process, the corresponding analysis should be made according to the specific climate area (SCZ, CZ, HSCW etc.). In addition, the range of indoor somatosensory temperature was determined based on the exponential weight continuous mean temperature of evaluation day, so as to obtain the grades of indoor thermal environment [79].

It is worthwhile pointing out that, the adaptive comfort standards mentioned above were all by the aid of outdoor temperature (outdoor monthly mean temperature, exponential weight continuous mean temperature, body sensing temperature, etc.) to define the indoor variable temperature set point. Compared with the previous fixed temperature set points for winter and summer, variable temperature standards could not only ensured comfort requirement, but also achieved energy conservation. According to relevant statistics, it could be saved approximately 10%-18% energy demand under the European climate conditions [81].

2.5 Summary

As afore-mentioned, this chapter mainly carried out the two kinds of research ideas on adaptive thermal comfort (namely adjustment PMV model and adaptive comfort model), and the current research status was summarized systematically by literature review.

Adjustment PMV model was used PMV value that predicted by steady-state heat balance theory to establish the actual thermal sensation of human beings in non-air conditioned buildings, and the specific revised methods were expressed as expectancy factor "e", adaptive coefficient "λ" and the △PMV (deviation between PMV and TSV). Fanger and Toftum [3] hold the opinion that thermal experience was the foundation of thermal preference in the future built environment. Meanwhile, climate and buildings were two major factors in creating psychological expectations (behavioral adaption can be fully explained by PMV model). In addition, adaptive coefficient "λ" proposed by R. Yao was adopting the static heat balance theory to establish the relationship between input and output of the model, which belonged to a black-box theory [8].

Adaptive comfort model was based on statistical method, and the comfort temperature or acceptable temperature range varied with outdoor climate. Which was based on the field investigation with a realistic background, emphasized the large-scale data collection and the use of statistical methods. Except for considering the interaction between occupants and environment, a wealth of behavioral, cultural and sociological factors were also taken into account seriously. It is no doubt that the mechanism reflected people's adaptability to climate to some extent, and the results in turn guided the design of indoor thermal environment in local regions. Compared with the thermal environment standard established based on laboratory research, this method has higher accuracy. Moreover, in the long course of human evolution, the auto-adaptive ability was the embodiment of human beings competing against nature and living in harmony with nature.

Above all, the present research mainly focuses on the Chinese typical climate conditions, by adopting the two representative models (adjustment PMV and adaptive model) to explore the building actual physical environment and the indoor thermal comfort.

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Chapter 3

RESEARCH METHODOLOGY

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3.1 Climate classification

Considering the importance of human-environment interaction in adaptive thermal comfort, the theory of which is mainly based on data observed in field surveys rather than climate chamber studies. Thus, a detailed climate classification is necessary for conducting related research. In this study, two methods of climate classification were carried out to improve the basic database of thermal comfort research in China.

3.1.1 Köppen-Geiger climate classification

The first quantitative classification of the world climates was presented by the German scientist W. Köppen in 1900, and it has been available as world map updated 1954 and 1961 by R. Geiger [1]. Köppen was trained as a plant physiologist and realized that plants are indicators for many climatic elements, therefore, five vegetation groups were carried out of the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E). A second letter in the classification considered the precipitation (e.g. Df for snow and fully humid), and a third letter the air temperature (e.g. Dfc for snow, fully humid with cool summer). Fig.3-1 showed the global distribution of climate, meanwhile, Table 3-1 and 3-2 presented specific criteria of the classification [2].

In Fig.3-1, it can be observed that China contained several types of the climate, such as BWk (36%), Dwa/Dwb (32%) and Cwa/Cfa (32%). Due to the clear boundaries and concise classification, this method had been widely used by numerous scholars.

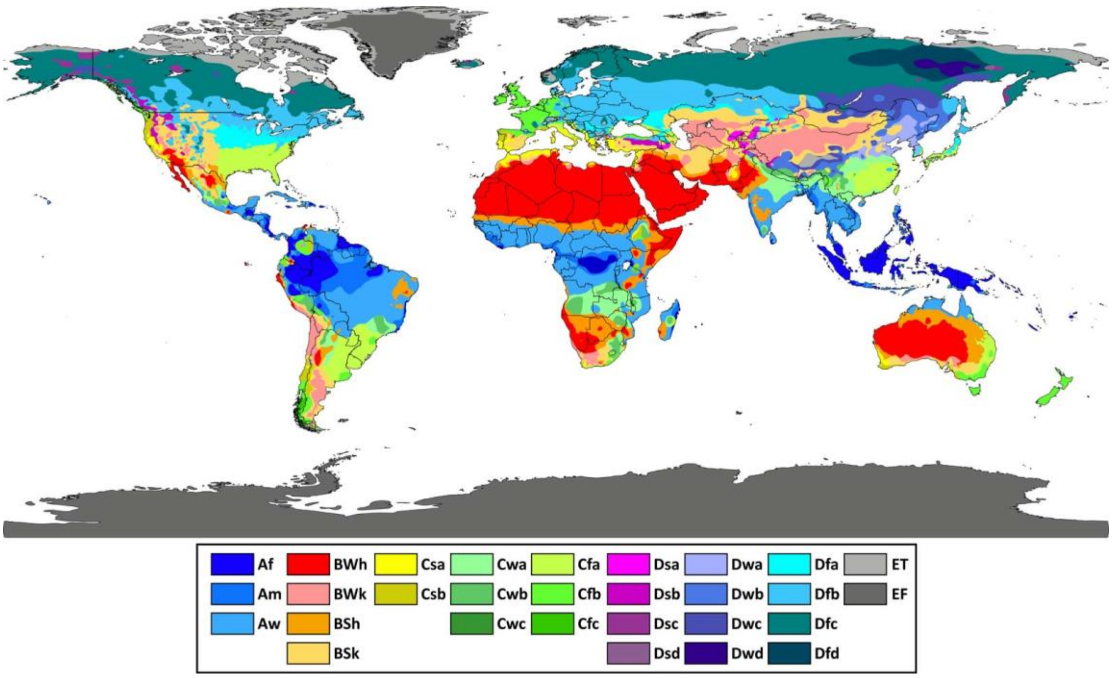

Fig. 3-1. Global climatic distribution with Köppen-Geiger method [1].

Table 3-1. The first two letters of the classification with Köppen-Geiger method [2].

Type	Description	Criterion
A	**Equatorial climate**	$T_{min} \geq +18°C$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60mm$
Am	Equatorial monsoon	$P_{ann} \geq 25(100-Pmin)$
As	Equatorial savannah with dry summer	$P_{min} < 60mm$ in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60mm$ in winter
B	**Arid climate**	$P_{ann} < 10P_{th}$
BS	Steppe climate	$P_{ann} > 5P_{th}$
BW	Desert climate	$P_{ann} \leq 5P_{th}$
C	**Warm temperate climate**	$-3°C < T_{min} < +18°C$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3P_{smin}$ and $P_{smin} < 40mm$
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climate**	$T_{min} \leq -3°C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3P_{smin}$ and $P_{smin} < 40mm$
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climate**	$T_{max} < +10°C$
ET	Tundra climate	$0°C \leq T_{max} < +10°C$
EF	Frost climate	$T_{max} < 0°C$

Note: for the polar climates (E) no precipitation differentiations are given, only temperature conditions are defined. This key implies that the polar climates (E) have to be determined first, followed by the arid climates (B) and subsequent differentiations into the equatorial climates (A) and the warm temperate and snow climates (C) and (D), respectively.

Table 3-2. The third letter of the classification with Köppen-Geiger method [2].

Type	Description	Criterion
a	Hot summer	$T_{max} \geq +22°C$
b	Warm summer	Not (a) and at least 4 $T_{mon} \geq +10°C$
c	Cool summer and cold winter	Not (b) and $T_{min} > -38°C$

d	Extremely continental	Like (c) but $T_{min} \leq$ -38℃
h	Hot steppe / desert	$T_{ann} \geq$ +18℃
k	Cold steppe /desert	$T_{ann} <$ +18℃

Note: (a) to (d) for the warm temperate and snow climates (C) and (D) and (h) to (k) for the arid climates (B). For type (b), warm summer, a threshold temperature value of +10℃ has to occur for at least four months.

3.1.2 Chinese climate regionalization

China's climatic classification could dates back to the early 1930s, which mainly including the climate regionalization (comprehensive climate zoning) and thermal design regionalization (single climate zoning).

In 1993, the standard of climatic regionalization for architecture (GB 50178-93) [3] was carried out. Taking the average temperature and relative humidity in January and July as the main indexes, and the annual precipitation and the number of days with the average daily temperature ≤5℃ and ≥25℃ as the auxiliary indexes, the whole country was divided into seven first-level regions. It mainly reflected the distribution characteristics of meteorological elements and their direct effect on buildings, furthered indicated the relationship between buildings and climate [4].

Another similar standard namely code for thermal design of civil building [5] was aiming at the average temperature of the coldest month (i.e. January) and hottest month (i.e. July) of the year as the main indexes, the days with degrees ≤5℃ and ≥25℃ as auxiliary indexes to divided the country into five regions: severe cold zone (SCZ), cold zone (CZ), hot summer and cold winter zone (HSCW), hot summer and warm winter zone (HSWW) and mild zone (MZ), as shown in Fig.3-2. It mainly reflected in the impact of meteorological elements on the building envelope.

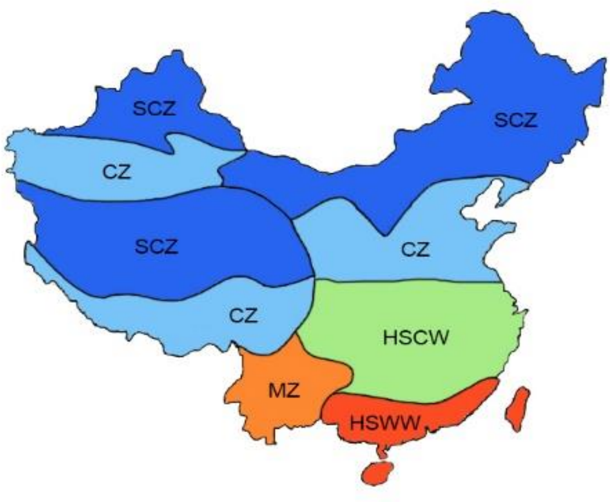

Fig. 3-2. Climatic thermal zone in China [5].

3.2 Field investigation of thermal comfort (adaptive comfort model)

3.2.1 Objective environmental measurement

The detail and accuracy of the data obtained from field investigation plays a decisive role on in-depth explanation of the thermal adaptability mechanism. Brager and de Dear [8] have divided the measurement standards of indoor environmental parameters into three levels according to the results of existing studies abroad, as shown in Table 3-3. From which in the third level, only air temperature and relative humidity were considered; the second level contained all the physical quantities in the steady-state PMV index that affect the evaluation of human thermal sensation; while the first level not only takes that physical quantities into account seriously, but also considered the influence of different horizontal heights on environmental parameters (0.1m for ankles, 0.6m for abdomen and 1.2m for head with people in sitting position).

Table 3-3. Different levels of measurement for indoor environmental parameters [8].

Level	Variables	Height of the measuring point
I	Air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, metabolic rate	Three different heights (0.1m, 0.6m, 1.2m)
II	Air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, metabolic rate	One height
III	Air temperature, relative humidity	One height

In the early studies of adaptive thermal comfort, numerous researchers [9,10] adopted the third-level test standard, however, the simple evaluation index could not helpful for in-depth analysis of the thermal adaptability. In current research, the objective environmental measurement shall at least reach the standard of the second level. And the specific requirements for environmental parameters are as following.

1) Category of measurement parameters

In this research, the indoor environmental parameters that to be measured were air temperature (T_a), black globe temperature (T_g), relative humidity (RH) and air velocity (V_a). Meanwhile, outdoor parameters including air temperature (T_a), relative humidity (RH), air velocity (V_a) and solar radiation (SR).

2) Measuring instruments

The measuring instruments in this study including T_a/RH thermometer recorder AZ-8828 (Fig.3-3a), black-ball thermometer WBGT-2010 (Fig.3-3b), point thermometer Raytek-ST (Fig.3-3c), anemometer TES 1341 (Fig.3-3d), solar intensity meter DaqPRO-5300 (Fig.3-3e) and diastimeter DISTO A5 (Fig.3-3f). AZ-8828 and Raytek-ST were mainly responsible for measurement of air temperature and relative humidity; WBGT-2010 measured the indoor black bulb temperature; air velocity and solar radiation were tested by TES 1341 and DaqPRO-5300, respectively; and DISTO A5 was responsible for other auxiliary dimensions. The details of instruments' parameters are shown in Table 3-4, meanwhile, the measuring range and precision were both meet the requirements of ISO 7726-2001 [11].

(a) (b) (c)

(d) (e) (f)

Fig. 3-3. The measuring instruments adopted in current research.

Table 3-4. The detail parameters of test instruments.

Parameters	Equipment	Type	Range	Accuracy
T_a	Thermometer recorder	AZ-8828	-40～85℃	±0.3℃
RH	Thermometer recorder	AZ-8828	0～100%	±3%
V_a	Anemometer	TES 1341	0～20m/s	±0.05m/s

T_g	Black-ball thermometer	WBGT-2010	0～80℃	±0.6℃
SR	Solar intensity meter	DaqPRO-5300	0～2000W/m^2	±3%
Meter	Range finder	DISTO A5	0～200m	±0.2m

3) Measuring position and time

- **Outdoor environmental parameters**

For outdoor environmental parameters, the dry bulb air temperature ($T_{a\text{-}out}$), relative humidity (RH_{out}) and air velocity ($V_{a\text{-}out}$) were tested by local meteorological station and thermometer recorder at the shading areas among target buildings, and solar radiation intensity (SR) was received by 8-channel data-logger (DaqPRO-5300) that using a circular probe with a diameter of 10cm attached to the building's façade, during the specific time started at 7:00 am to 20:00 pm for surveyed days.

- **Indoor environmental parameters**

For internal environmental parameters, the dry bulb air temperature ($T_{a\text{-}in}$) and relative humidity (RH_{in}) were measured by AZ-8828 thermometer recorder at the height of 0.6m, 1.7m and 3.3m above the ground, as shown in Fig.3-4; air velocity ($V_{a\text{-}in}$) was determined by Tes 1341 anemometer at the same place with $T_{a\text{-}in}$ and RH_{in}, and globe temperature ($T_{g\text{-}in}$) was recorded by adopting a 45mm black sphere at the height of 0.6m with its probe installed in the center of it (WBGT-2010).

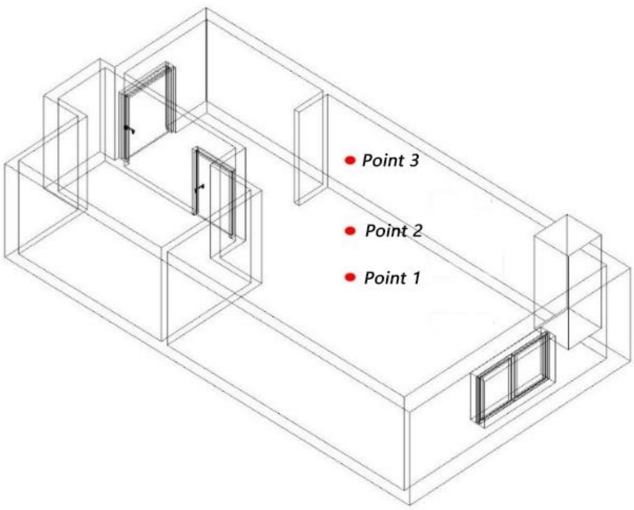

Fig. 3-4. Distribution of the measuring points.

3.2.2 Subjective questionnaire survey

The subjective survey was conducted simultaneously with the physical measurement, and the questionnaire was designed in simple and colloquial language which mainly including three modules as below.

1) Personal background

Module-1 collected occupants' fundamental data such as gender, age, height, weight, clothing and activity levels etc., the clothing insulation (clo) and metabolic rate (met) were estimated according to the recommended values in ASHRAE Handbook based on the survey results [12]. One thing needs to be pointed out that, since there were some differences between the description of the style and the fabric material of clothing in foreign countries and China, the insulation values by domestic scholars were also taken into account seriously [13-15], as listed in Table 3-5.

Table 3-5. Clothing insulation of single cloths (clo) [12].

Top outer garment		Bottom outer garment	
T-shirt (short)	0.09	Shorts	0.1
Long johns	0.15	Jeans	0.2
Shirts (long)	0.12	Pants	0.25
Jacket	0.25	Cotton trousers	0.3
Sweater	0.25	**Dress**	
Woolen vest	0.15	Thin dress	0.1
Coats		One-piece dress	0.15
Thin coat	0.3	Thick long dress	0.2
Suit	0.3	**Socks**	
Dust coat	0.4	Silk stockings	0.01
Down jacket	0.55	Thin cotton socks	0.02
Shoe		Thick cotton socks	0.05
Slippers	0.01-0.03	**Others**	
Sandals	0.02	Tie	0.01
High-heeled shoes	0.01-0.03	Silk scarves	0.02
Leather shoes	0.04	Cotton bib	0.05
Sports shoes	0.05	Hat	0.02-0.05
Cotton shoes	0.07	Gloves	0.05

When calculating the insulation of a set of clothes, it can be obtained from the individual garments, as shown in Eq.3-1. Where I_{cl} is the insulation of a set of clothes (clo) and $I_{cl,i}$ is the insulation of NO.i garment (clo).

$$I_{cl}=0.835\sum I_{cl,i}+0.161 \qquad (3\text{-}1)$$

Moreover, when occupants were sitting on a chair, it would increase the thermal resistance below 0.15clo to the human body. The specific value depended on the contact area between the chair and the human body, which could be estimated by Eq.3-2. Where $\triangle I_{cl}$ is the additional insulation caused by the contact between chair and body (clo), and A_{ch} is the contact area between the seat and body (m^2).

$$\triangle I_{cl} = 0.748A_{ch} - 0.1 \qquad (3\text{-}2)$$

In this study, occupants were all sitting and engaged in light work. Based on the reference value in ASHRAE Handbook [12], the human metabolic rate was set as 1.1met. However, it is necessary to know the activities of the occupants within 30 minutes before the survey. If the respondents were engaged in physical labor (such as going downstairs, running, etc.), it is impossible to judge whether the metabolic rate of the respondents had recovered to a stable state at that time. Therefore, such survey samples should be excluded in the data analysis.

2) Evaluation of thermal environment

Module-2 regarded the occupants' thermal cognitive status, including the thermal/humidity/air-velocity sensation votes (TSV/HSV/ASV), thermal/humidity/air-velocity preference votes (TPV/HPV/APV), thermal/humidity/air-velocity acceptability votes (TAV/HAV/AAV) and overall comfort votes (OCV). From which 7-point scale (-3 to 3) was adopted to evaluate sensation and preference votes, and 5-point scale (-2 to 2) was for acceptability and overall comfort votes [16,17], as shown in Fig.3-5 to Fig.3-8.

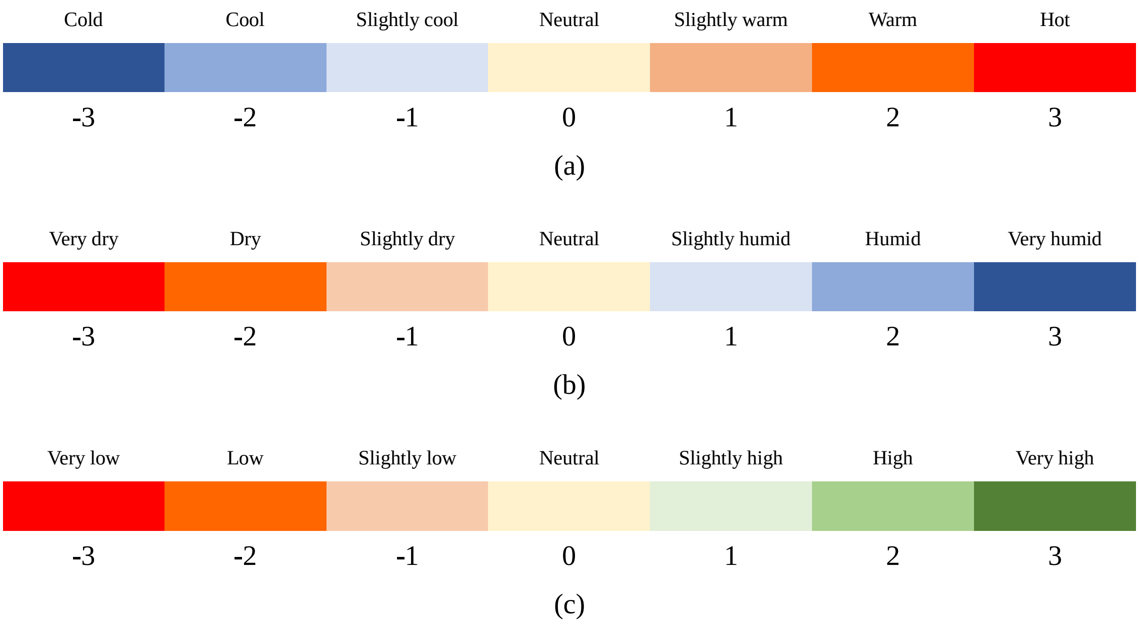

Fig. 3-5. Subjective 7-point sensation scale: (a) thermal sensation scale; (b) humidity sensation scale; (c) air velocity sensation scale.

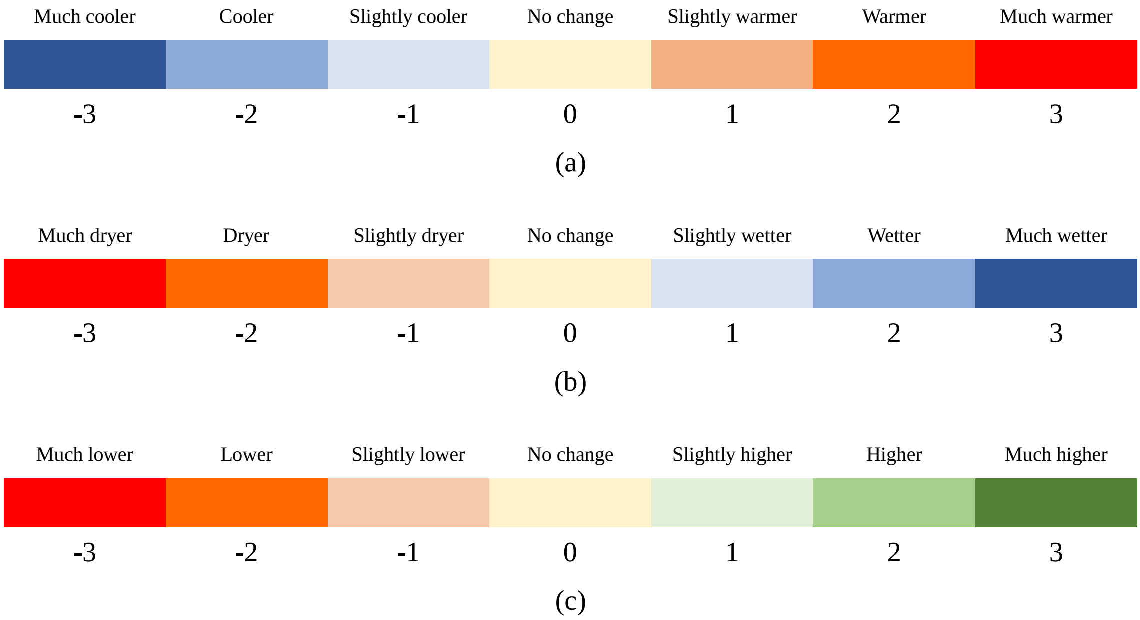

Fig. 3-6. Subjective 7-point preference scale: (a) thermal preference scale; (b) humidity preference scale; (c) air velocity preference scale.

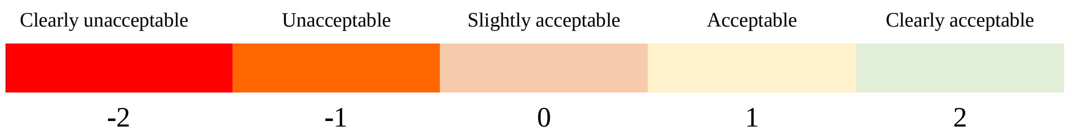

Fig. 3-7. Subjective 5-point thermal/humidity/air velocity acceptability scale.

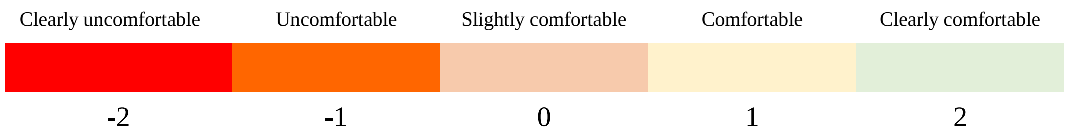

Fig. 3-8. Subjective 5-point thermal/humidity/air velocity overall comfort scale.

3) Behavior regulation

Module-3 determined human adaptive behavior to avoid thermal dissatisfaction and generally taken two aspects into account: one is the transformation of room physical parameters such as adopting shading measures, raise/lower the design temperatures of HVAC, operating the exterior fenestration and using fans, the other is auto-adaptive actions that covers changing clothing and activity levels, as well as drinking iced beverages etc.

3.3 Simulation study of thermal comfort (adjustment PMV model)

Numerical simulation is a method developed with the gradual improvement of computer performance, and it is widely used in various fields at present. One of the remarkable characteristics is that could set different boundary conditions to simulate various environmental conditions. In this study, the simulation method that based on the thermal balance and PMV-PPD model was adopted to explore the quantitative and qualitative relationships between energy consumption and thermal comfort. Considered of PMV model was mainly focus on the steady-state environment, in other words, it may ignore the psychological and physiological effects of subject's comfort state over the time. Thus, the adjustment PMV model (APMV) was used instead of original equation so as to reduce the error caused by the calculation results.

In view of the coupling effect of energy saving and thermal comfort, the software of Energy-Plus was adopted in current research. As a dynamic simulation approach of building energy consumption, it was first carried out by U.S. Department of Energy in 1996 and takes advantage of BLAST and DOE-2 with adding many advanced functions [6]. The basic assumption was that the room air temperature was uniform as well as the temperature of building envelope surfaces. By calculating the heat transfer of the envelope under the heat disturbance at each time step, the thermal performance of the whole building can be calculated, such as the heating/cooling loads and indoor air temperature. In addition, due to the fact that building exterior envelopes (outer wall and roof) are always in contact with the outside environment, the envelope heat transfer is a three-dimensional unsteady process, therefore, the most crucial issue is to solve the rule of temperature and heat flow field changing with time. In this study’s simulation process, the new solution contained elements that are called conduction transfer functions (CTFs), which are used to calculate the unsteady heat transfer of the building envelope [7]. The thermal characteristic of the building is separated from the external disturbance and the response coefficient is considered to be the thermal characteristic of the envelope itself, as long as the reaction coefficient of the building and instantaneous/historical values of the disturbance are known, it can calculate the heat flow at that time.

To be specific, firstly, the applicability and simulation accuracy of the software were verified; secondly, according to the local energy conservation codes, five typical benchmark geometric models were established in Open Studio (Sketch-Up plug-in) for sites representative of various climates, meanwhile, adopting the engine of Energy-Plus (EP-Launch) to calculate the instrument definition file (IDF), respectively; thirdly, based on the optimal strategies for each regions, a further analysis of thermal comfort was calculated to narrow the optimal interval mentioned above, so as to achieve the final unity of energy saving and thermal comfort. It is worthwhile mentioning that, the simulation study in this study was one of the adaptive thermal comfort research methods (adjustment PMV model--APMV), and the detail information of another method (adaptive comfort model) have been introduced in the section above (sec. 3.2).

3.4 Evaluation index and processing method

The original data obtained through the field investigation are mostly individual and scattered, and cannot be directly used to reflect the overall regularity. Therefore, it is necessary to classify the data for later statistical analysis and comparison. The specific evaluation indexes and processing method in this study are listed as following.

3.4.1 Indoor operative temperature

As for indoor thermal environment, although the air temperature (T_a) can be easily received from on-site measurements. However, due to the special regional climate, the influence of radiation heat transfer on human thermal comfort should not be neglected. Hence, the operative temperature (T_o) which takes both air temperature (T_a) and mean radiant temperature (T_{mrt}) into consideration is deemed as a more accurate evaluation indicator. The calculation method of which was stipulated in GB/T 50785 [18]: when the air velocity was less than 0.2m/s or the difference between T_{mrt} and T_a was less than 4℃, T_o can be approximately equal to the weighted average value of the T_{mrt} and T_a, with the calculation process according to the Eq.3-3.

$$T_o = A \times T_a + (1 - A) \times T_{mrt} \qquad (3\text{-}3)$$

where T_o is operative temperature (℃), T_a is air temperature (℃), T_{mrt} is mean radiant temperature (℃) and A is constant with its value is related to indoor air velocity, see Table 3-6 for details. Due to the clear physical meaning and convenient practical application conditions, T_o was often chosen for field research of thermal comfort by multiply scholars.

Table 3-6. Recommended value of constant A.

Air velocity (m/s)	<0.2	0.2-0.6	0.6-1.0
A	0.5	0.6	0.7

3.4.2 Outdoor prevailing mean temperature

The theory of adaptive thermal comfort model emphasized the time variability of occupants' comfortable setting point, especially with the change of outdoor temperature [19]. Therefore, the prevailing mean outdoor temperature (T_{pma}), as an exponentially weighted mean value which taken the history temperatures' distribution into account, was calculated according to the algorithm in ASHRAE Standard [17] and EN 15251 [20], shown as Eq.3-4.

$$T_{pma} = (1 - \alpha)\,(T_{od\text{-}1} + \alpha T_{od\text{-}2} + \alpha^2 T_{od\text{-}3} + \cdots + \alpha^6 T_{od\text{-}7}) \qquad (3\text{-}4)$$

where T_{pma} is prevailing mean outdoor temperature (7 days ago) (℃); α is a constant varying from 0 to 1, which reflects the rapid response degree of continuous mean change for outdoor temperature, the value of 0.6-0.9 is recommended according to ASHRAE-55 Standard [17]; T_{od-1} is the average daily outdoor temperature on the previous day (°C); T_{od-2} is the average daily outdoor temperature before 2 days (°C), etc. It is important to note that, the current day's mean outdoor temperature is not used in the equation mentioned above, the primary reason is the highest temperature of current day is not obtained until 15:00 pm.

3.4.3 Neutral temperature

Academics considered the state of lukewarm as the "thermal-neutral", or defined as the condition in which subjects are neither willing to be warmer nor colder, and the neutral temperature (T_n) corresponds to the temperature at which most subjects feel thermal comfort. In current research, T_n is mainly calculated in two ways as below.

1) Linear regression method

The most commonly method for calculating neutral temperature is linear regression analysis. The thermal sensation vote (TSV) observed in the field survey was taken as the dependent variable, and the corresponding operative temperature (T_o) as the independent variable, with the general form of the equation can be expressed as Eq.3-5. Where TSV is thermal sensation vote, T_o is operative temperature (°C), a is regression coefficient and b is intercept. When TSV is equal to zero, the corresponding T_o is the neutral temperature (T_n), and the regression coefficient reflects sensitivity of occupants' thermal sensation to temperature variation.

$$TSV = a \times T_o + b \qquad (3\text{-}5)$$

Due to the diversity and complexity of the factors that affecting the thermal sensation, if the regression was directly carried out between thermal sensation obtained on field investigation and the corresponding temperature, although the regression equation obtained was statistically significant, the correlation coefficient was usually low. Therefore, in practice, numerous scholars adopted mean thermal sensation (MTSV) to replace the actual TSV. To be specific, the operative temperature in each voting and the corresponding thermal sensation votes were counted, meanwhile, the mean value of operative temperature and thermal sensation in each temperature interval were calculated according to the interval of 0.5°C (Bin method) [21], and finally to establish the regression analysis between the $T_{o,\,mean}$ and MTSV, as shown in Eq.3-6. Where MTSV is mean thermal sensation votes, $T_{o,\,mean}$ is mean operative temperature (°C), a is regression coefficient and b is intercept. The neutral temperature could be achieved when MTSV equals to zero.

$$MTSV = a \times T_{o,\,mean} + b \qquad (3\text{-}6)$$

2) Griffiths constant method

In order to get the neutral temperature out of a relatively small sample, Griffiths [22,23] suggested to use a simple standard value (G) as the linear regression coefficient between thermal sensation vote and operative temperature, that is, if the mean thermal sensation vote and mean operative temperature were achieved during the investigation period, the neutral temperature could be easily acquired, as shown in Eq.3-7.

$$T_n = T_{o,\,mean} + (0 - MTSV) / G \qquad (3\text{-}7)$$

where T_n is neutral temperature (°C) (also called Griffiths comfort temperature), $T_{o,\,mean}$ is mean operative temperature (°C), MTSV is mean thermal sensation votes and the G is Griffiths constant. Griffiths comfort temperature had been explored for three different Griffiths constant values (0.25, 0.33 and 0.50), as investigated by P. Tewari [24], Z. Wu [25], M.A. Humphreys [26] and H.B. Rijal [27]. In this study, the value of 0.50 was adopted for further calculation mainly because there was almost no difference between mean globe temperature (TSV=0) and the neutral temperature.

3.4.4 Preferred temperature

Thermal preference for indoor environment refers to occupants' psychological expectation that the indoor temperature would increase, decrease or stay at the current level. In the present study, preferred temperature was determined by adopting probit analysis, which only dealt with binary form of response to a variable. Based on probit analysis, the thermal preference votes were arranged in three ways: “prefer warmer”, “prefer cooler” and “no change”. From which the “prefer warmer” and “prefer cooler” indicated that the subjects felt dissatisfied with the current indoor environment, and “no change” referred to satisfaction. The probit regression model was then used to estimate the lowest probability of obtaining thermal preference votes for a warmer or cooler environment. Consequently, the most likely temperature in which a preference for no temperature change were found. Ordinal regression was adopted using probit as the link function and operative temperature as the covariate. The mean temperature (probit=0) were calculated by dividing the constant by the regression coefficient. The inverse of the probit regression coefficient was the standard deviation of the cumulative normal distribution. All the probits were transformed into proportions by using the following function, as expressed in Eq.3-8.

$$\text{Probability} = \text{CDF. NORMAL (quant, mean, S.D.)} \qquad (3\text{-}8)$$

where CDF. NORMAL is the cumulative distribution function for the normal distribution, quant is the operative temperature (°C) and S.D. is standard deviation. And the preferred temperature is the point at which the two curves intersected.

3.4.5 Acceptable temperature range

It is no doubt that the width of the comfort zone depended on a balance between thermal satisfaction and dissatisfaction, in other words, the effectiveness and feasibility of adaptive opportunities determined the acceptable temperature range [28]. Due to the individual differences, there were 5% of the occupants felt dissatisfied when PMV equaled zero. Therefore, the acceptable temperature range was defined as an interval which could meet the requirement by 80% or 90% of the occupants. In this study, two methods were adopted for achieving the acceptable temperature range as following.

1) Indirect process

Indirect process considered that the occupants were satisfied with current environment when responses voted between ±1 range (“slightly cooler”, “neutral” and “slightly warm”) of thermal sensation scale. Researches indicted that there were approximately 20% and 10% of the subjects not satisfied with surrounding environment when predicted mean votes of ±0.85 and ±0.5, respectively. Putting the relationship of PMV-PPD applied to the regression model of the thermal sensation could be obtained 80% and 90% acceptable temperature range.

2) Direct process

For direct method, typical questions were set in the questionnaire for occupants: “Could you accept the thermal environment at the moment?” Meanwhile, to calculate the occupants' percentage of acceptance rate within each temperature interval, and then adopting multiple regression method to determine the relationships between acceptance rate and operative temperature. For some regions with specific climate conditions, thermal sensation votes (TSV) were not in the neutral state when actual percentage of dissatisfied (APD) was lowest, instead, it was asymmetrically distributed on both sides of TSV＝0. Therefore, the APD and PPD were all calculated with 0.5℃ binned data against the indoor operative temperature respectively to obtain the 80% and 90% acceptable temperature interval in this research.

3.4.6 Adaptive approach

As afore-mentioned, the strong relationship between prevailing mean outdoor temperature (T_{pma}) and indoor neutral temperature found by Humphreys lays a solid foundation for the adaptive theory. And the relationships between that two parameters (adaptive comfort model) could be expressed as in Eq.3-9.

$$T_{pma} = a \times T_o + b \qquad (3\text{-}9)$$

Compared with the PMV model that established by steady-state heat balance method, adaptive comfort model was not used to predict comfort sensation or responses, but to explore the relationships between thermal sensation and environmental parameters in people's long-term process. And these research results all indicated that the neutral temperature and outdoor temperature were significantly correlated with the local climate characteristics. In early thermal adaptive models, since few researchers recorded outdoor weather data during the field investigation, the monthly mean outdoor temperature was mainly derived from local meteorological data. However, the prevailing mean outdoor temperature (T_{pma}) adopted in adaptive model for current research referred to the half-life period in nuclear physics and medicine, the average outdoor temperature of a day during the investigation period was related to the average temperature of the previous days, and the calculation method is shown in Eq.3-4.

Considering the field investigation involved in this study, the prevailing mean outdoor temperature (T_{pma}) was adopted as the outdoor temperature index in Chapter 5 and Chapter 6 to establish the relevant thermal adaptive comfort model.

3.5 Summary

On the basis of reasonable climate classification, this chapter mainly introduced the research methods of adaptive thermal comfort: field investigation and simulation study, which the mathematical algorithm were based on adaptive comfort model and adjustment PMV model, respectively. For exploring the thermal comfort in actual buildings, a large number of field investigations were essential to expound the regular relationships between environmental parameters and human subjective responses, so as to provide a reliable reference for the design of building thermal environment. The content of the field investigation mainly including environmental measurement and questionnaire survey. In addition, the original data and evaluation indexes obtained from the field survey were given in a detailed description, and systematically introduced the calculation process of basic parameters involved in the following chapters.

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Chapter 4

INVESTIGATION STUDY ON ADAPTIVE THERMAL COMFORT IN EVAPORATIVE COOLING AIR CONDITIONED BUILDINGS

Content

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4.1 Introduction

4.1.1 Motivation

With the acceleration process of China's urbanization, building technology brings with it new threatens, for instance, efficient urban construction loses sight of the trade-off relationships between energy demand and thermal comfort, a large amount of conventional energy is used at the expense of environmental protection etc. [1-4]. For sake of creating a more comfortable indoor environment, the Heating, Ventilation and Air Conditioning (HVAC) system consumed approximately 50% of building energy in more than half a century when it was widely used [5]. Furthermore, the refrigerant in which is the key offender for polluting the environment. Thus, the exploration of indoor adaptive thermal comfort under the background of cleaner and sustainable energy is put on the agenda.

4.1.2 Description of evaporative cooling air conditioned system

Evaporative cooling air conditioned system (ECS), as a truly sense of passive sustainable cooling technology, had been widely focused in recent years. The operation mechanism of which is based on the distinction between wet and dry bulb air temperature, through the process of liquid-vapor conversion by water (transforming sensible heat to steam enthalpy), thereby resulting the temperature reduction in the system [6-7]. Since the cold source (water) is not only affordable and accessible but also with none of the CFCs utilization, which eliminate the human long-term concern for ozone layer destruction [8]. According to relevant statistics, ECS system has a lower cost of cooling equipment with an initial investment of approximately 50% comparing to the conventional HVAC, meanwhile, the operating energy consumption is around 20% of normal level, promoting the energy-saving rate achieve to 70%-80% [9-10]. With the possession of high efficiency, economically benefits, energy conservation and environmental friendly, it had been extensive used in the regions that characterized by dry-hot climate in summer such as China, Kazakhstan, Turkey, Iran and other “the Belt and Road” (B＆R) developing countries.

4.1.3 Scientific Originality

The innovation of this part is the first attempt to adopt field investigation, subjective responses and objective measurements for exploring the occupants' authentic thermal sensations as well as the adaptive models for public buildings with evaporative cooling systems in China. Furthermore, a new concept of appropriate area for predicted model is proposed under the real condition, through quantitating the optimal interval of predicted model by former researchers, the relationships between thermal comfort and physical environment indexes can be systematically summarized so as to fill in the gaps for correlational research.

4.1.4 Target of the work

With issues mentioned above, the purpose of the current chapter mainly lie upon five points as following, with the overall workflow as shown in Fig.4-1.

- To probe authentic indoor physical environment and actual thermal comfort in ECS buildings in Urumqi during summer season.
- To determine occupants' neutral (comfort) temperature, preferred temperature and acceptable temperature ranges in ECS buildings.
- To establish the adaptive model of human sensation considered the specific climatic conditions.
- To search the appropriate usage intervals of adjustment predicted models in ECS buildings.

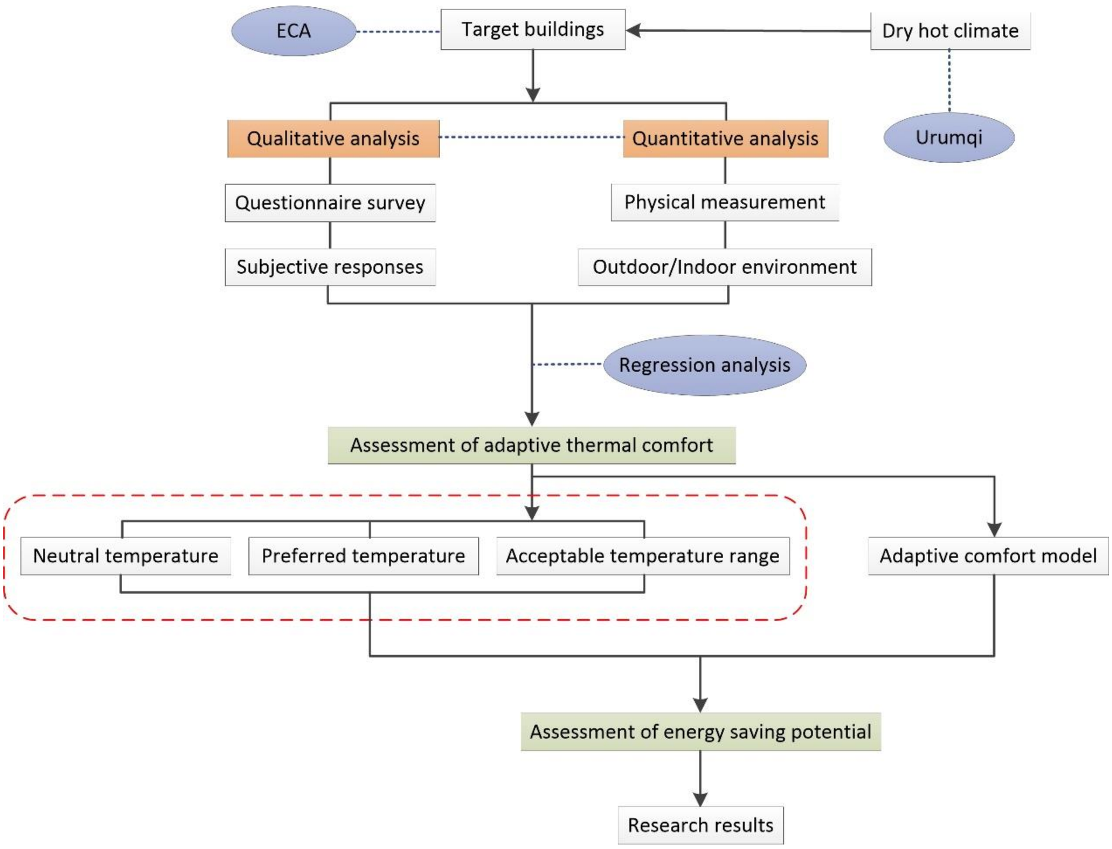


Fig. 4-1. Workflow of investigation study in Urumqi.

4.2 Overview of the field investigation

4.2.1 Location and regional climatic condition

The survey site of this work is in Urumqi, the capital of Xinjiang autonomous region which is located in the northwest of China (latitude: 43.47°N, longitude: 87.37°E and elevation: 917.9m above mean sea level) [11]. Based on Köppen-Geiger climate classification, Urumqi can be classified into cold desert climate zone (Bwk) [12], with the characteristic of dry-hot in summer and dry-cold in winter, as shown in Fig.4-2. The hottest period throughout the year is from June to August with maximum outdoor temperature of up to 38.4℃ and the coldest period is from December to February with minimum temperature of up to -12.6℃ (Fig.4-3, 4-4), the maximum difference between outdoor wet and dry bulb temperature in summer can reach approximately by 15.7℃. Meanwhile, due to the intense solar radiation and sparse precipitation (less than 200mm/year), Urumqi experiences a dry-hot climate in summer with lower relative humidity which the mean value roughly equals to 45.5%. Therefore, the insufficient moisture in the atmosphere throughout the year, especially in summer, can lead to thermal discomfort (such as dehydration) due to the higher skin evaporation.

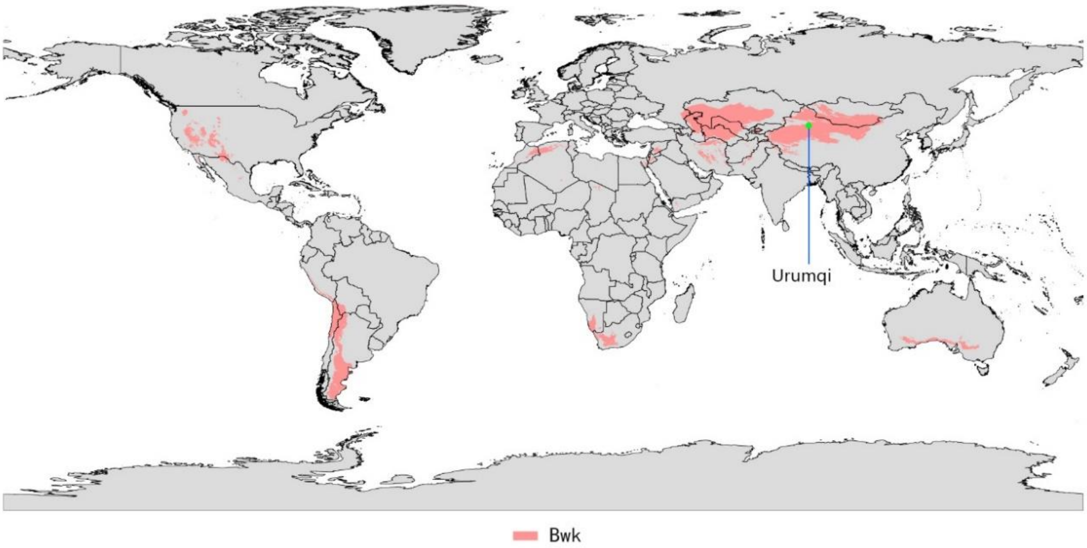


Fig. 4-2. Survey site in Köppen-Geiger climate classification.

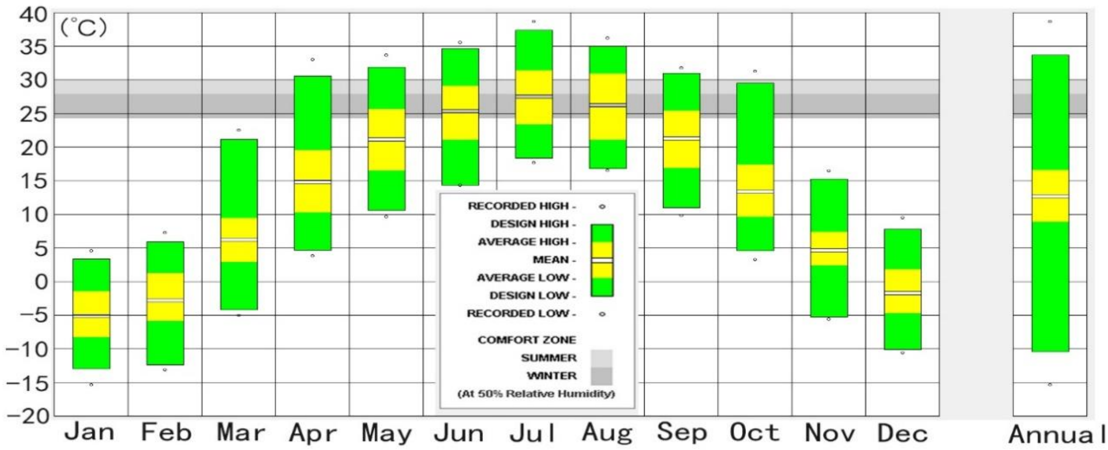


Fig. 4-3. Annual air temperature and relative humidity in Urumqi.

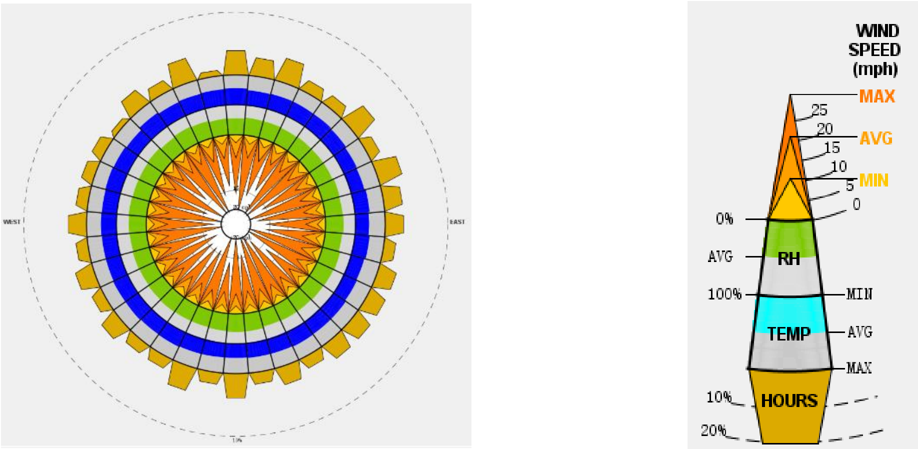


Fig. 4-4. Annual wind speed in Urumqi.

4.2.2 Aimed buildings characteristics

The target buildings in current part are all located in Urumqi, which are the autonomous region hospital of traditional Chinese medicine, center office building of Midong thermal power plant and Urumqi training base. Meanwhile, the testing spaces are all standard rooms with the main principle of selection as following: 1) there should have similarity or consistency in the use of new energy systems (refer to ECS); 2) the occupants' usage rate should be as high as possible so as to minimize the accidental error of measuring results; 3) the indoor thermal environment indexes required by subjects were in substantial agreement. Also, the construction of which were steel-framed concrete with the holistic heat transfer coefficient (U-value) for roof and exterior wall can be calculated by thermal physical property parameters of each layer material [13], in doing so, the consequences approximately by 0.2 - 0.32W/(m^2 K) and 0.3 - 0.4 W/(m^2 K) respectively; the transparent envelope adopted double glazing with a vacuum layer, possessing solar heat gain coefficient (SHGC) and total heat transfer coefficient (U-value) by 0.5-0.65 and 1.8-2.2 W/(m^2 K), respectively.

In addition, the building mentioned above are both equipped with direct evaporative cooling systems (DEC) or two stage direct/indirect evaporative cooling systems (TSEC) for indoor thermal comfort. From which the DEC system consisted of a fan at the front side of the unit and a re-circulating pump to circulate water to the upper side of the cooling pad. TSEC unit consisted of an indirect cooling module (ICM) heat exchanger for indirect cooling of primary air stream followed by direct evaporative cooling via direct cooling module (DCM) made of cellulose based honeycomb cooling pads. Fig.4-5 and Table 4-1 present the technical specifications of the evaporative cooling systems. Continuous use of fans (wall mounted or ceiling) was common in the surveyed buildings. These fans facilitate the convective cooling along with the existing evaporative cooling systems. During the investigation, windows and doors could be flexibly controlled to facilitate the effect of indoor ventilation, as well as exhausted damp air out.

Table 4-1. Geographical data of selected cities.

Parameter	DEC	TSEC
Supply airflow	2845	1650
Exhaust airflow	--	320
Cooling media type	Aspen pads	Cellulose pads
Cooling media dimensions	90cm×60cm×2.8cm	ICM: 80cm×60cm×40cm
		DCM: 80cm×60cm×20cm
Power rating	360W	600W
Outer casing material	Galvanized steel sheet	Fibre-reinforced plastic
Water sump capacity	120	50

Note: DEC is direct evaporative cooling systems and TSEC is two stage direct/indirect evaporative cooling systems

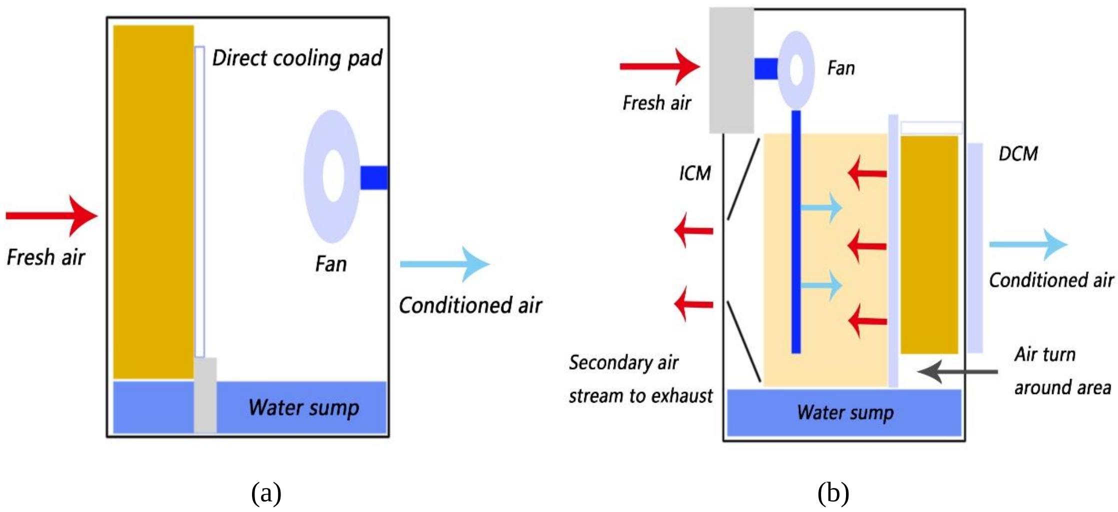


Fig. 4-5. Pictorial view of evaporative cooling system: (a) DEC; (b) TSEC.

4.2.3 Subjective questionnaire survey

The original plan of this work is to hand out 600 questionnaires and actually received 577 valid datasets, which consisted of 328 males and 249 females. One thing needs to be pointed out that, the selected subjects all lived in Urumqi for several years and had adapted to the local climate as well as the indoor environment of buildings. The questionnaire form mainly composed of three parts as below: section-A considered the basic background of participants such as gender, age, height, weight etc., due to the clothing insulation cannot be easily and directly calculated for most of the time, the values are estimated based on ASHRAE Standard-55 [14], and the metabolic rate is also determined according to the corresponding activity levels in that norm, the statistical results are shown in Table 4-2; section-

B collected occupants' subjective thermal responses which including thermal sensation vote (TSV), thermal expectative vote (TEV), thermal comfort vote (TCV) and thermal acceptability vote (TAV), ASHRAE seven-point scale was used for recording TSV, TEV and TCV, TAV was evaluated by five-point scale to describe the overall indoor thermal satisfaction [15,16]; section-C regarded human adaptive behavior to avoid thermal dissatisfaction and generally taken two aspects into account: one is the transformation of room physical parameters such as adopting shading measures, raise/lower the design temperatures of ECS, operating the exterior fenestration and using fans; the other is auto-adaptive actions that covers changing clothing and activity levels, as well as drinking the iced beverages etc.

Table 4-2. Summary of background information of investigated subjects.

Gender	Number	Categories	Age (--)	Height (cm)	Weight (kg)	CI (clo)	BSA (m^2)	BMI (kg/m^2)	MR (met)
Male	328	Max.	58	190.2	94.0	0.66	2.21	28.8	1.8
	~~(340)~~	Min.	15	162.0	48.0	0.25	1.52	15.6	1.0
		Mean	26.2	174.8	71.3	0.35	1.75	22.2	1.1
		S.D.	5.5	6.8	9.2	0.07	0.15	2.6	0.13
Female	249	Max.	55	173.0	74.0	0.71	1.88	23.5	2.0
	~~(260)~~	Min.	13	151.0	42.0	0.28	1.35	15.1	0.9
		Mean	24.8	162.2	51.5	0.38	1.54	19.5	1.1
		S.D.	5.8	4.9	11.1	0.09	0.15	2.1	0.18
Total	577	Max.	58	190.2	94.0	0.71	2.21	28.8	2.0
	~~(600)~~	Min.	13	151.0	42.0	0.25	1.35	15.1	1.0
		Mean	25.6	169.5	63.5	0.36	1.67	21.4	1.1
		S.D.	5.6	5.4	10.4	0.09	0.15	2.7	0.14

Note: CI represents clothing insulation; BSA represents body surface area; BMI represents body mass index; MR represents metabolic rate; Max./Min. represents maximum/minimum and S.D. represents standard deviation.

4.2.4 Objective environmental measurements

Physical measurements were conducted simultaneously with the questionnaires that initiated from July to August 2017, the test period started at 7:30 am to 19:30 pm during investigation days, as shown in Fig.4-6. From which the outdoor physical parameters covering air temperature (T_a), relative humidity (RH), air velocity (V_a) and solar radiation intensity (SR). Meanwhile, indoor parameters containing air temperature (T_a), black globe temperature (T_g), relative humidity (RH) and air velocity (V_a), which were all tested by calibrated instruments, and the sampling time of instruments was 10 min after it became stable. The details of instruments' parameters had introduced in chapter 3, and the average and standard deviation values of all measured data are counted for further analysis (section 5.3 and 5.4).

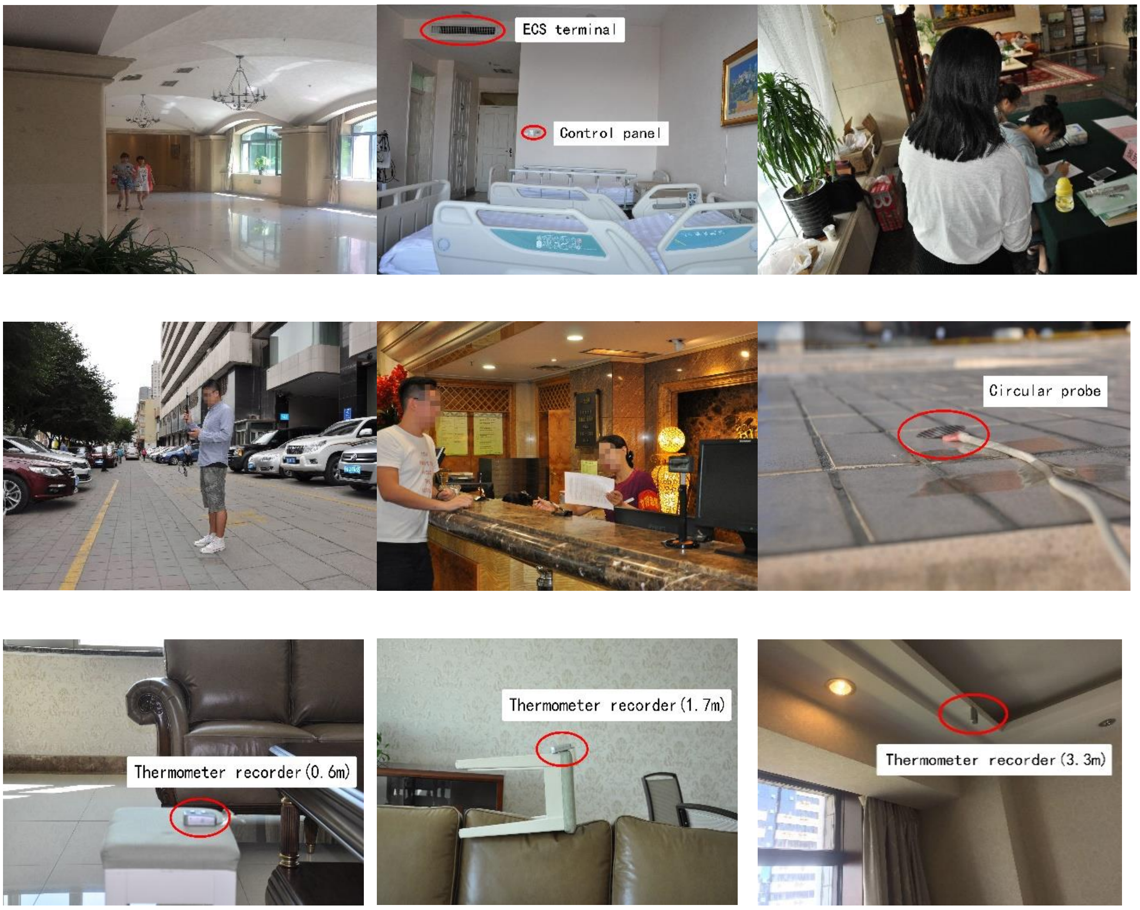


Fig. 4-6. Buildings and indoor environment during the investigation period.

4.3 Assessment of various indoor adaptive comfort parameters

4.3.1 Objective thermal environment

1) Variation of outdoor thermal environment

The details of outdoor thermal environmental parameters during field surveys are presented in Table 4-3, which can be discovered that the outdoor air temperature in Urumqi city ranged from 26.8℃ to 38.2℃, with the mean and standard deviation (S.D.) values of 36.2℃, 3.4℃, respectively, the higher temperatures in summer mainly due to the intensity solar radiation, especially in 15:00-16:30 pm that can reach approximately by 262.2w/m^2. Outdoor relative humidity oscillated between 16.5% and 56.8%, and less than 40% for most of the time (mean=36.6%, S.D. =5.1%). Except for the outdoor instantaneous air speed values of some specific period is large (≥3m/s), the mean and S.D. values were 0.68 m/s, 0.65 m/s respectively.

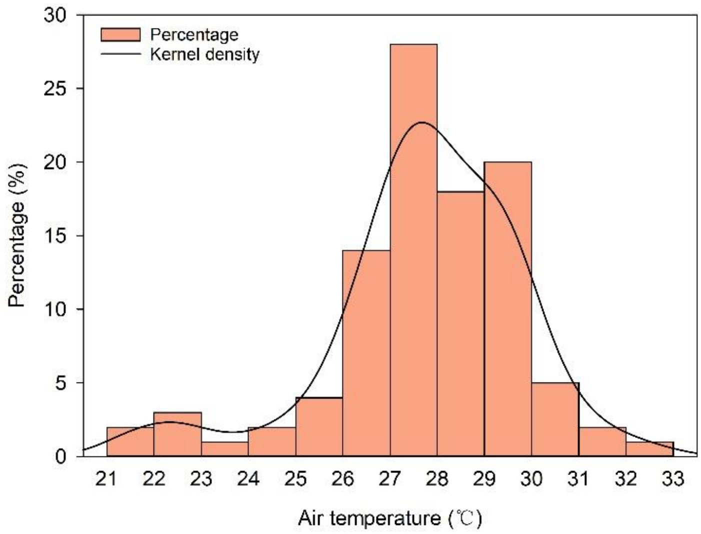
Table 4-3. The measured results of environmental parameters.

Variables	Unit	Height	Max.	Min.	Mean	S.D.
Outdoor air temperature ($T_{a\text{-}out}$)	℃	1.2m	38.2	26.8	36.2	3.4
Outdoor relative humidity (RH_{out})	%	1.2m	56.8	16.5	36.6	5.1
Outdoor air velocity ($V_{a\text{-}out}$)	m/s	1.2m	3.6	0.08	0.68	0.65
Solar radiation (SR)	w/m^2	--	262.2	2.4	142.8	185.6
Indoor air temperature ($T_{a\text{-}in}$)	℃	0.6m	31.2	21.6	27.7	1.7
		1.7m	31.5	21.4	28.2	1.6
		3.3m	32.8	22.1	28.5	1.3
Indoor relative humidity (RH_{in})	%	0.6m	86.5	24.5	62.8	11.1
		1.7m	85.0	26.2	63.7	11.0
		3.3m	90.2	27.5	63.6	10.5
Indoor air velocity ($V_{a\text{-}in}$)	m/s	0.6m	1.5	0	0.16	0.21
		1.7m	1.8	0.02	0.14	0.25
		3.3m	2.0	0.02	0.22	0.18
Black globe temperature (T_g)	℃	0.6m	32.6	22.8	29.1	1.6

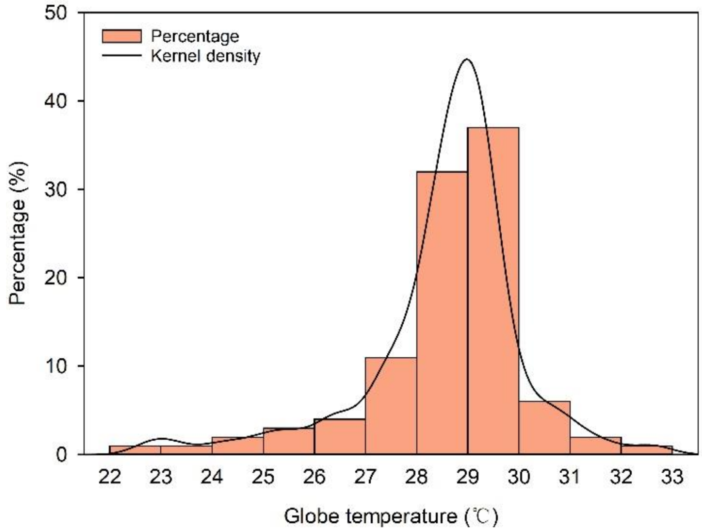
Note: Max./Min. represents maximum/minimum; S.D. represents standard deviation.

2) Variation of indoor thermal environment

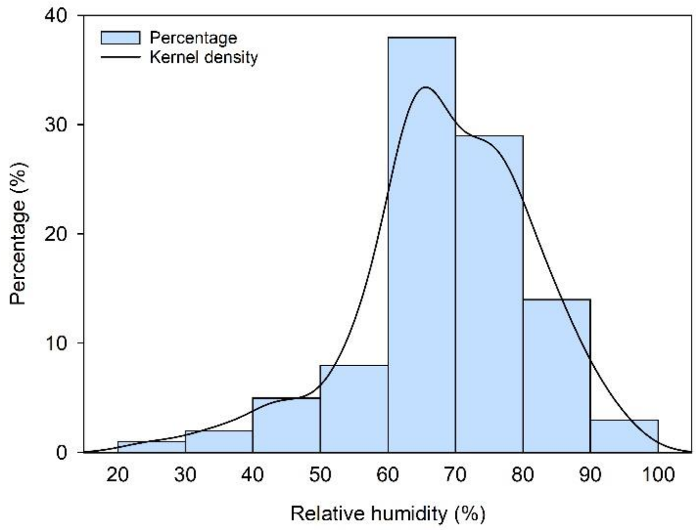
In terms of indoor thermal environment, the rooms being tested were all controlled by evaporative cooling air conditioned systems (ECS) in summer, and Table 4-3 summarized the different values of measured environmental parameters. Comparing with Fig.4-7(a), the variation of indoor air temperatures were mainly distributed from 26℃ to 30℃ and maximum value even exceeded 32.5℃. As the height increased, the temperatures rises slightly, and around 75% of the values were higher than 27℃ which surpassed the neutral (comfort) temperatures in other previous studies; as for globe temperature, shown in Fig.4-7(b), were slightly higher than air temperature due to the coupling effect of radiation and convection was considered, the highest frequency varied from 27℃ to 31℃ with the average and S.D. value of 29.1℃, 1.6℃ respectively; Fig.4-7(c) showed the variation of indoor relative humidity in summer, as the ECS reduced air temperature by absorbing heat through evaporation and the process carried large amounts of moisture into the ambient air, thus the mean values of RH located at a higher level (approximately 60%-90%) than NV [17], AC [18] and MM [19] buildings; Fig.4-7(d) presented the variation of indoor air velocity in summer, the values were basically between 0.14m/s and 0.23m/s, about over 50% of which were below 0.2m/s, the primary reason is easy to be affected by outdoor environment and always maintained in a steady state, which generally satisfied the reference in ASHRAE-55 Standard [14].


Percentage
Kernel density
Percentage (%)
Air temperature (℃)

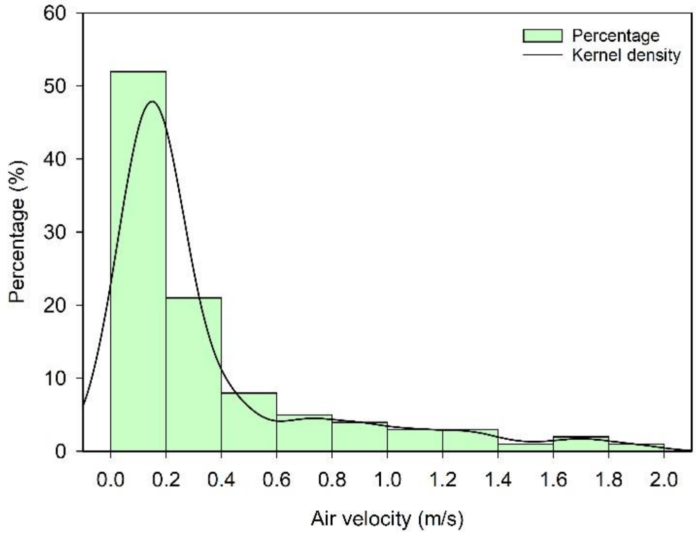
(a)


Percentage
Kernel density
Percentage (%)
Globe temperature (℃)

(b)


Percentage
Kernel density
Percentage (%)
Relative humidity (%)

(c)

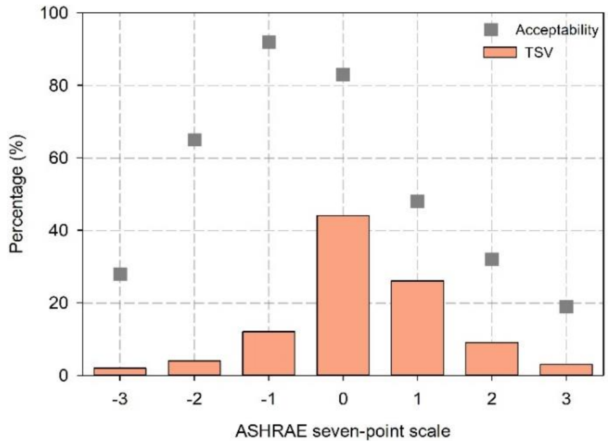


(d)

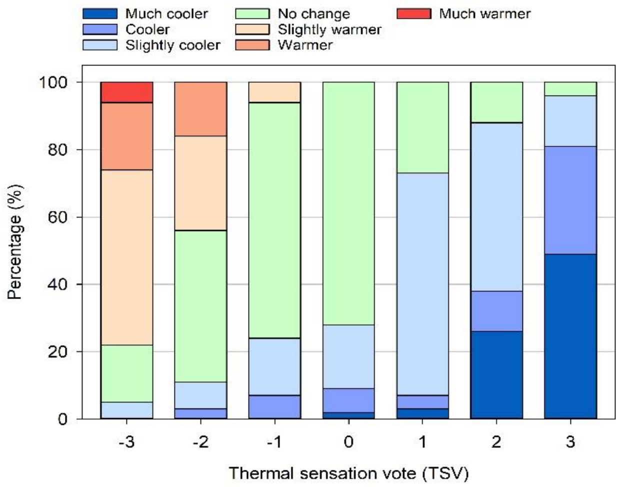
Fig. 4-7. The distribution of indoor thermal environmental parameters: (a) air temperature; (b) globe temperature; (c) relative humidity; (d) air velocity.

4.3.2 Subjective thermal responses

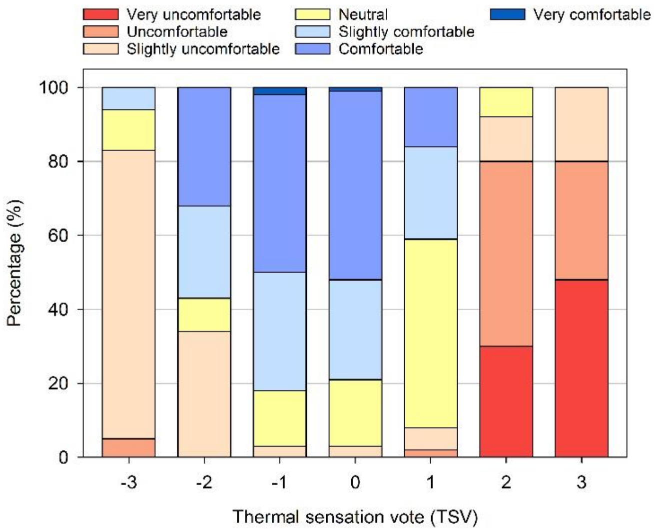
Fig.4-8(a) shows the results of thermal sensation vote (TSV) and overall thermal acceptability vote (TAV) in each TSV interval, the highest percentage of votes were neutrality (TSV＝0) which approximately by 44%, and beyond 80% of the occupants' TSV were distributed in comfort bandwidth (±1). The proportion of thermal acceptability were all surpass 80% when TSV scale is “slightly cool” (－1) and “neutral” (0), and less than 50% at the warmer side (1 to 3), which illustrated that subjects were inclined to cooler indoor environment to warmer one in summer. In terms of thermal expectation vote (TEV), Fig.4-8(b) summarized the proportion of ingredient for TEV in each TSV scale, the percentage of cooler preference (the sum of “slightly cooler”, “cooler” and “much cooler”) maintained an upward trend with the level of TSV increased from －3 to 3, while the warmer appeals were gradually declined, the highest votes of “no change” occurred when TSV equals 0 that approximately by 72%, and still had 28% of the occupants preferred a cooler environment in this scale, the outcomes indicated the neutral state (TSV＝0) was not always the best strategy for all participants, and the variation between thermal sensation and expectation may existed to some extent, which also confirmed the basic conclusion of previous studies by Z. Wu [20], R. Thapa [21], S.A. Damiati [22] and M.K. Singh [23]. Based on the coupling effect of indoor air temperature, relative humidity and wind speed, the overall thermal comfort vote was presented in Fig.4-8(c), neutrality and comfort state (including slightly comfortable, comfortable and very comfortable) were all exceeding 90% between －1 and 1, although a significant proportion of subjects expected a cooler environment when TSV equals 1, there were still around 51% and 41% of the people feel neutral and comfortable, which further revealed that the perennial living conditions had improved the heating resistance of local residents in summer.



(a)



(b)



(c)

Fig. 4-8. Subjective responses: (a) thermal sensation vote and thermal acceptability; (b) thermal expectative vote in each TSV interval; (c) overall comfort vote in each TSV interval.

4.3.3 Neutral (comfort) temperature

1) Linear regression analysis

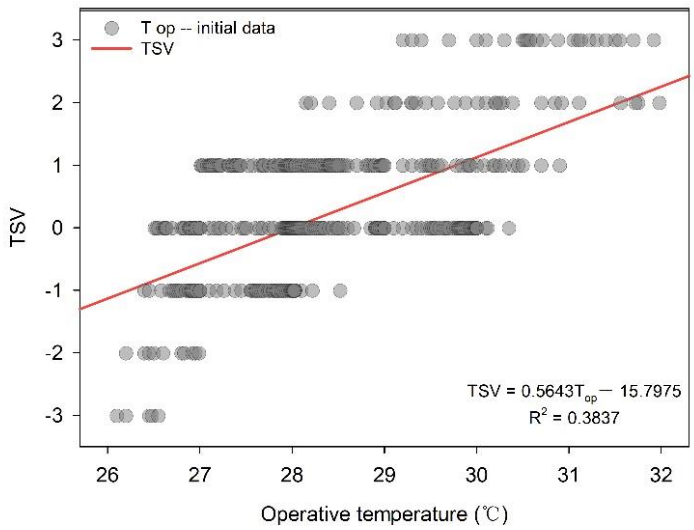
To explore the critical point at which occupants feel neither too cold nor too hot, neutral temperature, also known as comfort temperature, is carried out by linear regression analysis between indoor operative temperature (T_{op}) and thermal sensation vote (TSV), and T_c is determined when TSV equals to zero. The initial data of TSV and T_{op} is collected in Fig.4-9(a), from which can obtain the regression equation as Eq.4-1, the slope of fitted curve is 0.5643, which illustrated that approximately 1.78°C modification in T_{op} would lead to one unit change in TSV.

$$TSV = 0.5643T_{op} - 15.7975 \ (R^2 = 0.3837, \ p < 0.05) \qquad (4\text{-}1)$$

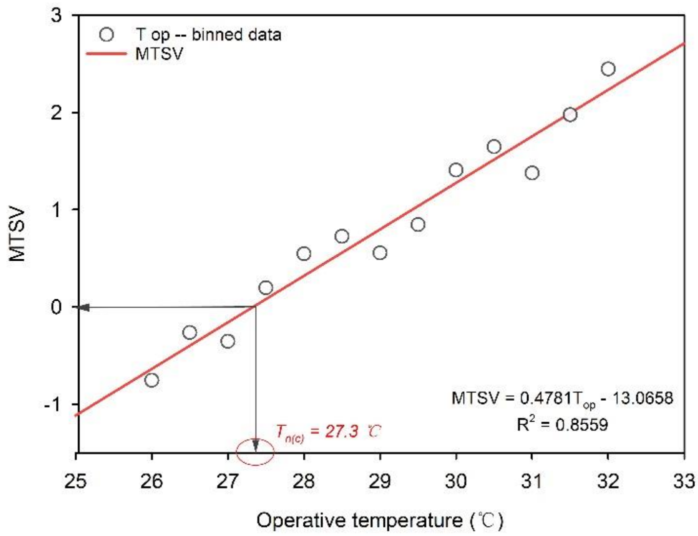
Furthermore, considered of diversity of factors that affecting thermal sensation and the differences among individuals, numerous researchers had adopted mean thermal sensation vote (MTSV) instead of TSV [24-26]. In current research, by setting the binned data at 0.5°C interval of T_{op} to receive the linear regression model between $T_{op(mean)}$ and MTSV. As shown in Fig.4-9(b), MTSV is well fitted with T_{op}, and the specific linear equation is as following Eq.4-2.

$$MTSV = 0.4781T_{op} - 13.0658 \ (R^2 = 0.8559, \ p < 0.05) \qquad (4\text{-}2)$$

It is obviously to find out that, with comparing the neutral temperature obtained by direct regression analysis (T_c=27.9°C), the outcomes calculated by bin method (T_c=27.3°C) were basically agree with that, but the determination coefficient (R^2) has increased significantly, which is also consistent with the model assumptions by C. Fu [27] and regarded as a reasonable value, meanwhile, it is slightly higher than the results of AC, NV and MM mode due to the specific local climate and psychosomatic adaption.



(a)



(b)

Fig. 4-9. Regression analysis between operative temperature and thermal sensation vote: (a) initial data; (b) binned data.

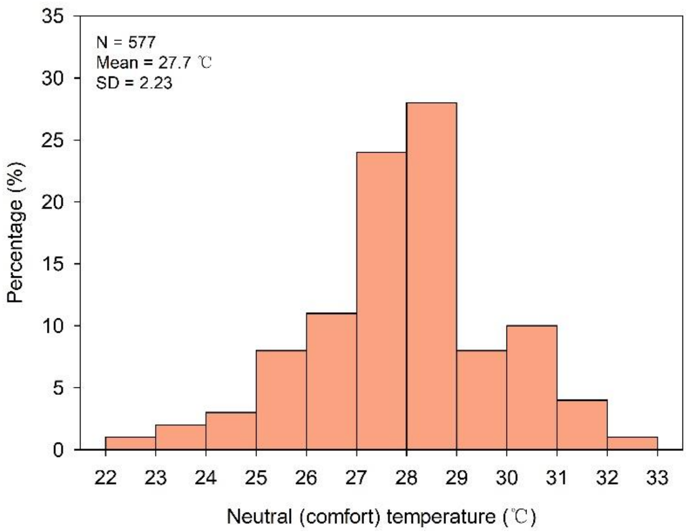


Fig. 4-10. The frequency distribution of Griffiths neutral temperature (G＝0.5).

2) Griffiths constant method

On account of the limitations of experimental conditions, this part applied Griffiths constant method to further calculate the indoor comfort temperature in summer for avoiding the errors caused by relatively small sample size. It recommends adopting a simple standard value as a linear regression coefficient (Griffiths constant) between thermal sensation vote and operative temperature, and three empirical values (0.25, 0.33 and 0.50) had been probed in previous studies. In current study, the value of 0.50 was adopted for further calculation mainly because there was almost no difference between mean globe temperature (TSV＝0) and comfort temperature. Fig.4-10 summarized the distribution of indoor comfort temperature with the binned data of 1℃ by that method, the comfort temperature interval ranged from 22℃ to 33℃ and above 80% of the values were scattered across in 26℃ to 30℃. In addition, the mean value of comfort temperature was 27.7℃, which is basically similar with the results that were calculated by linear regression (27.3℃).

4.3.4 Preferred temperature

As afore-mentioned, there might be disparity between neutral temperature and preferred temperature. In other words, occupants generally prefer warmer state than neutral one in cold climate, and pursuit cooler condition in hot climate, which also had been confirmed in former studies [20,28]. In this part, binned method with half-degree-Celsius and weighted linear regression analysis were adopted to evaluate the indoor preferred temperature, all of the thermal responses were divided into two groups: namely "prefer warmer" (TEV＞0 ＋ half votes of "no change") and "prefer cooler" (TEV＜0 ＋ half votes of "no change"). In addition, we calculated the percentage of votes in "prefer warmer" and "prefer cooler" for each 0.5℃ interval respectively, and then regressing against with the corresponding operative temperature to obtain two regression models. Fig.4-11 presents the results of preferred temperature for investigated ECS buildings, with the related regression equations are shown as Eq.4-3 and Eq.4-4.

$$P\ (\text{prefer warmer}) = -0.0671T_{op} + 1.9521\ (R^2 = 0.8397,\ p < 0.001) \qquad (4\text{-}3)$$

$$P\ (\text{prefer cooler}) = 0.0893T_{op} - 2.2014\ (R^2 = 0.8653,\ p < 0.001) \qquad (4\text{-}4)$$

Based on Fig.4-11, the value of indoor expectative temperature (T_e) appeared at the intersection point of two fitting equations, which was 26.6℃ in this work, and it was approximately by 0.7℃ lower than neutral (comfort) temperature (27.3℃ by linear regression), the deviation between T_e and T_c was smaller than previous study by C. Fu [27] (1-3℃) and J.M.Y. Tse [28] (0.4-1.9℃), which is mainly due to the occupants' higher physiological adaptation to local dry-hot climate in summer.

4.3.5 Acceptable temperature interval

For exploring the value limitation of acceptable temperature range, typical questions were set in the questionnaire: "Could you accept the environment at the moment?" Meanwhile, to calculate the occupants' percentage of acceptance rate within each temperature interval, and then adopting multiple regression method to determine the relationships between acceptance rate and operative temperature. As discussed above, TSV was not in the neutral state when actual percentage of dissatisfied (APD) was lowest. Instead, it was asymmetrically distributed on both sides of TSV＝0. Therefore, the APD and PPD were all calculated with 0.5℃ binned data against the indoor operative temperature respectively in Fig.4-12, and the regression models were presented as Eq.4-5 and Eq.4-6.

$$PPD = 1.85T_{op}^2 - 97.83\, T_{op} + 1306.18\ (R^2 = 0.9344,\ p < 0.001) \qquad (4\text{-}5)$$

$$APD = 3.4071T_{op} - 83.4964\ (R^2 = 0.7826,\ p < 0.001) \qquad (4\text{-}6)$$

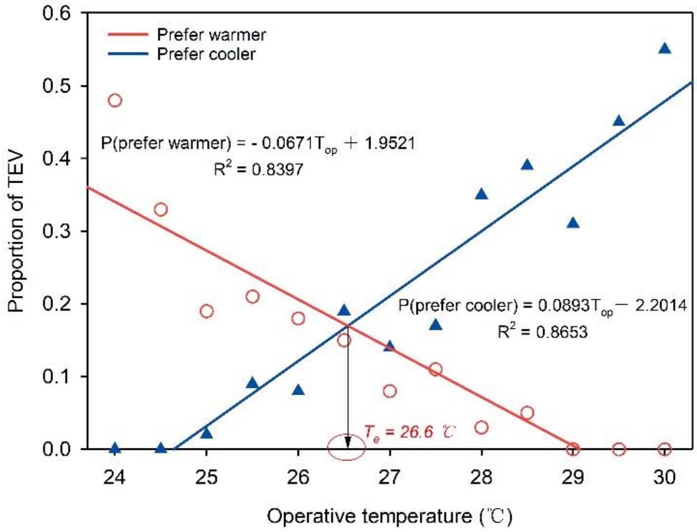


Fig. 4-11. Regression analysis of preferred temperature.

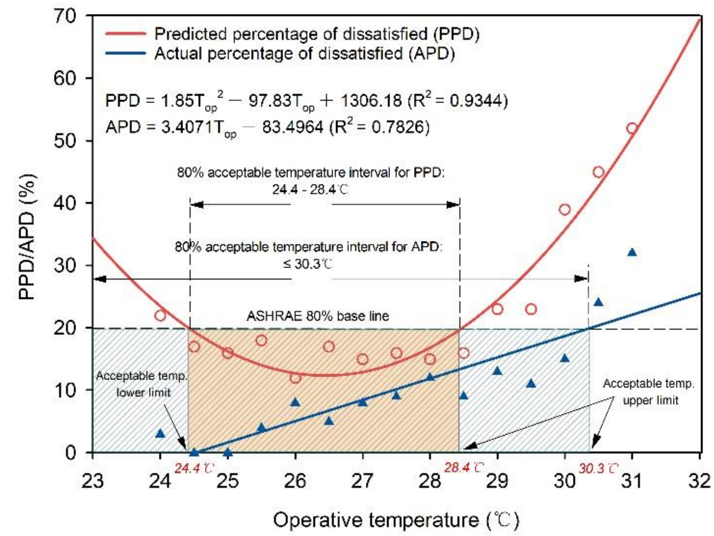


Fig. 4-12. Acceptable temperature interval determined by APD and PPD.

According to ASHRAE-55 [14], the acceptability limitation of 80% had been defined as evaluation criteria to receive the indoor acceptable temperature interval, the predicted limitation of 80% acceptable interval was 24.4-28.4℃, while the upper limit of actual situation was 30.3℃, 1.9℃ higher than that calculated by PPD. The wider bandwidth temperature acceptability illustrated that the local occupants with higher climatic adaptation, and the conventional PMV-PPD model underestimated the subjects' heating tolerance in summer.

4.3.6 Thermal adaptability

Thanks to conventional predicted model (PMV-PPD) cannot reflect the objective situation accurately, it is meaningful to further analyze the quantitative relationships of body thermal adaptability. Generally speaking, adaptive regulation of human body mainly involves three aspects: behavioral, psychological and physiological adaption [29,30]. Although the behavioral adaptions could be easily obtained via questionnaire survey, psychological and physiological adjustment need to be judged by a long-term process and past experience. Therefore, this section focused on the relationships between three adaptive mechanisms mentioned above and indoor/outdoor temperature. From which the part 1 discusses about behavioral adaptions, and adaptive thermal comfort model that considered the coupling relationships among psychological and physiological adaption was carried out in part 2.

1) Physical and auto-adaptive behavior

Behavioral adaptions includes actions that taken intentionally or unintentionally to change one's thermal equilibrium, which can be divided into physical adjustment (use curtains/blinds, switch on/off ECS, etc.) and auto-adaptive actions (such as transform clothing, change activity levels etc.). Fig.4-13 summarized the intent frequency of seven common modes of behavioral regulations when subjects felt hot in summer with evaporative cooling systems, the top three choices that surpassed the base line of 50% were reducing set point of ECS temperature, changing clothing and decreasing activity levels with the consequence approximately of 85.8%, 68.4% and 57.5% respectively. Although the use of equipment could satisfy the compensation requirements of thermal comfort, a large amount of energy would be wasted by operating windows/doors at irregular times.

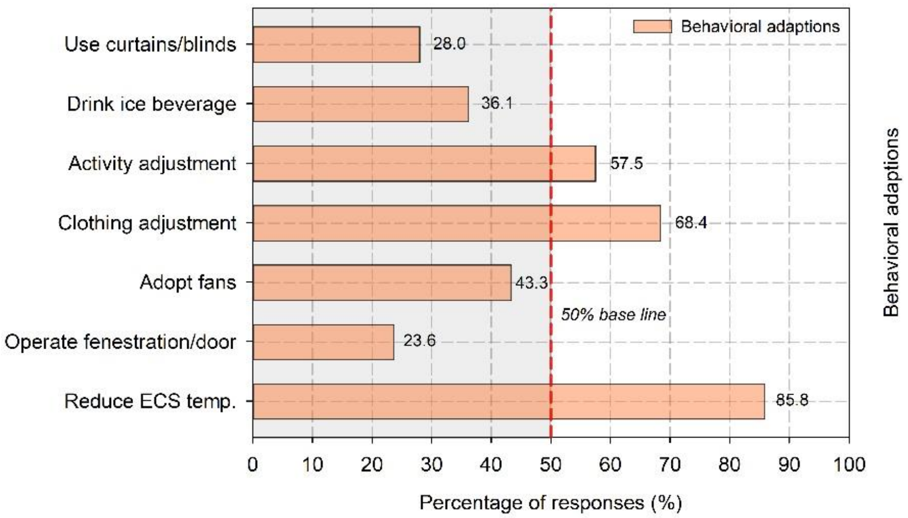


Fig. 4-13. The intent frequency of behavioral adaptions.

With grouping the indoor operative temperature by 0.5℃, the mean T_{op} and the corresponding average clothing insulation of each group were calculated respectively in Fig.4-14. It can be easily found that there existed a negative correlation between T_{op} and clothing insulation regardless of male or female, but the slope was slightly different. 1℃ increase in T_{op} could lead to 0.013clo and 0.010clo decrease in clothing insulation for male and female respectively, the tiny deviation reflected the men with slightly greater dependence on clothing than women in this region.

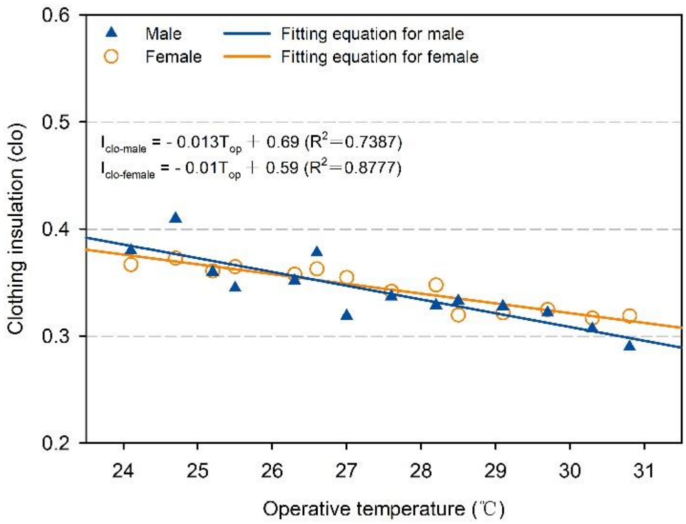


Fig. 4-14. The relationship between operative temperature and clothing insulation.

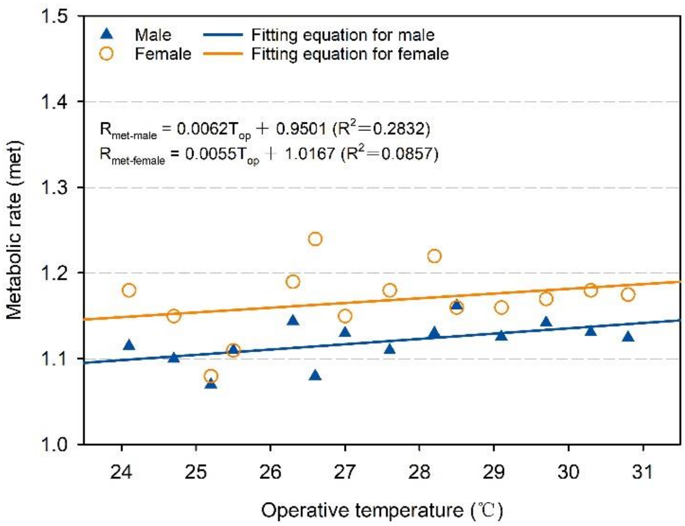


Fig. 4-15. The relationship between operative temperature and metabolic rate.

Due to the thermal discomfort can be effectively regulated by changing activity levels, the relationship between T_{op} and metabolic rate was also probed with the same method, as shown in the Fig.4-15. The subjects mostly maintain the sitting position with light physical activity during the period of investigation, and based on ASHRAE-55 [14], the metabolic rate was defined as M≤ 1.2met ($70W/m^2$), from the results of weighted linear regression, there's no obvious linear relationship between T_{op} and metabolic rate as the determining coefficient (R^2) of fitting equation was 0.2832 and 0.0857 for male and female respectively, which further manifested that metabolic rate is more influenced by various activity levels rather than surrounding environmental parameters.

2) Establishment of adaptive comfort model

For adaptive approach indicted that the importance of long-term life experiences' thermal sensation and environmental parameters, R.J. de Dear [31] and J.F. Nicol [32] explored the relationships between prevailing mean outdoor temperature (T_{pma}) and comfort temperature, confirmed that the T_{pma} is a more accurate index than outdoor instantaneous climatic values. Therefore, in current part, the adaptive model for occupants in dry-hot region with ECS was established by adopting regression analysis among T_c (mainly refer to $-1 \leq TSV \leq 1$) and T_{pma} (average temperature at the matching time with each T_c, which ranged from 26.8°C to 38.2°C according to the related algorithm. Fig.4-16 showed the relationships between indoor operative temperatures (comfort scatters) and prevailing mean outdoor temperature, with the linear fitting formula presented as Eq.4-7.

$$T_c = 0.06T_{pma} + 26.17 \ (R^2 = 0.3686,\ p < 0.001) \qquad (4\text{-}7)$$

In accordance with the theory of thermal acceptability, there are 80% and 90% acceptable rate limits corresponding to PMV of ±0.85 and ±0.5 [33], the four indicators were applied in this study to explore the regression model. And from Fig.4-16, the equations of the lower and upper limits of 80% and 90% acceptable indoor comfort temperatures were obtained as Eq.4-8 to Eq.4-11.

$$T_{80\%,UL} = 0.06T_{pma} + 27.95 \qquad (4\text{-}8)$$

$$T_{80\%,LL} = 0.06T_{pma} + 24.39 \qquad (4\text{-}9)$$

$$T_{90\%,UL} = 0.06T_{pma} + 27.21 \qquad (4\text{-}10)$$

$$T_{90\%,LL} = 0.06T_{pma} + 25.13 \qquad (4\text{-}11)$$

Through the calculation, two indoor acceptable operative temperature interval (refer to 80% and 90%) were received by approximately 1.78°C (interval/2, i.e., 3.56°C/2) and 1.04°C (interval/2, i.e., 2.08°C/2) respectively. As the prevailing average outdoor temperature increased, optimal comfort temperature were also added slightly and mainly distributed from 27.1°C to 28.9°C for 90% limit area. Meanwhile, the slope of lower/upper limits equations were basically consistent with that adaptive model. Although the regional differences (climate, culture, physiological characteristics, etc.) may lead to adaptive models varying from other researches, it provided a comparative reference for the definition of comfort zones in current norms of ASHRAE-55 [14].

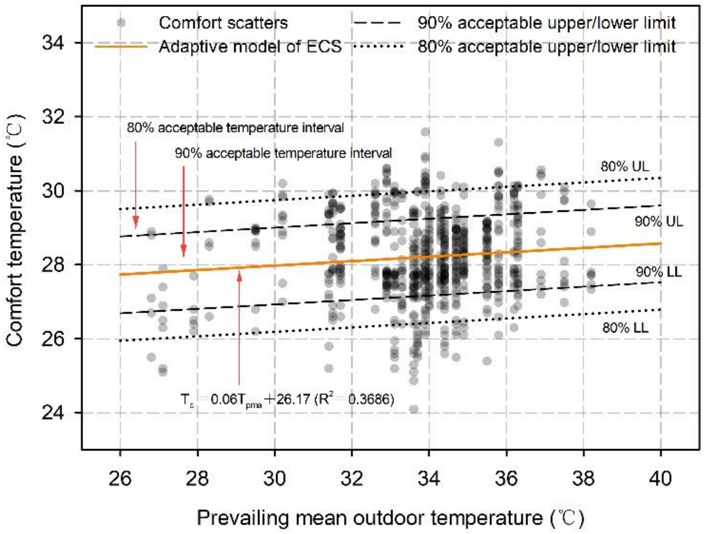


Fig. 4-16. The relationship between indoor comfort temperature and prevailing mean outdoor temperature in summer.

4.4 Discussion

4.4.1 The comparison of PMV and adaptive model in ECS buildings

As mentioned above, the “comfort zone method” proposed in ASHRAE-55 was according to the algorithm of PMV model, which defined a typical indoor thermal environment with 80% acceptability (based on 10% overall and 10% partial thermal comfort dissatisfaction). In current research, the indoor air velocity were distributed between 0.14m/s and 0.23m/s for most of the time with average value of approximately 0.17 m/s, lower than the upper limit specified in ASHRAE-55 (still air of 0.2m/s). In addition, the mean value of physical activity 1.1met with clothing insulation 0.36clo were also conform with the basic requirement in that standard (1-1.3met, less than 0.5clo respectively) [14]. Hence, the data of indoor operative temperature with specific humidity ratio in ECS buildings were recorded to compare with the thermal comfort zone in ASHRAE-55, for questing the relationships between adaptive model and original PMV algorithm.

As shown in Fig.4-17, the indoor air state parameters were determined by operative temperature (X-axis) and relative humidity with a certain amount of moisture content (Y-axis), and there were scarcely comfort dots distributed within the recommended comfort zone (light orange shaded area). Most of which were scattered across the upper limit of ASHRAE-55, the wider acceptable temperature interval with higher relative humidity in ECS buildings was beyond the recommended zone, which further suggested that the PMV model adopted in ASHRAE-55 cannot be an appropriate method for assessing ECS buildings in Urumqi. The root causes of deviation mainly lie upon three aspects as follows: firstly, the thermal comfort (coupling effect) and thermal neutrality (TSV＝0) were regarded as the same concept during the process of establishing PMV model. However, the former described a coupling effect of behavioral, psychological and physiological sensations, which was difficult to adopt a certain fixed parameter for judging the comfort evaluation. In other words, PMV model based on thermal neutrality may exist inevitable limitations on the predicted results to some extent. In addition, the heat dissipated of evaporation in heat balance equation by PMV takes the comprehensive influence of four indexes into account, namely heat loss by skin vapor diffusion (E_{sv}), heat loss by sweat diffusion (E_{sd}), heat loss by latent respiration (E_{lr}) and heat loss by dry respiration (E_{dr}) [34]. Nevertheless, the calculations of mean skin surface temperature (T_{sk}) and sweat evaporation were both made under the assumption that within the range of thermal neutral state, T_{sk} and E_{sd} were fixed values because they were only affected by metabolic rate. And thus, the PMV equation cannot accurately reflect the offset of thermal comfort when occupants felt uncomfortable at some special period, such as the process of sweating profusely. Lastly, although it gave full consideration to the six major factors affecting thermal comfort, the uniqueness of the subjects did not cover the degree of climatic adaptation and self-regulation for local occupants in different regions, which was also a significant cause of that deviation.

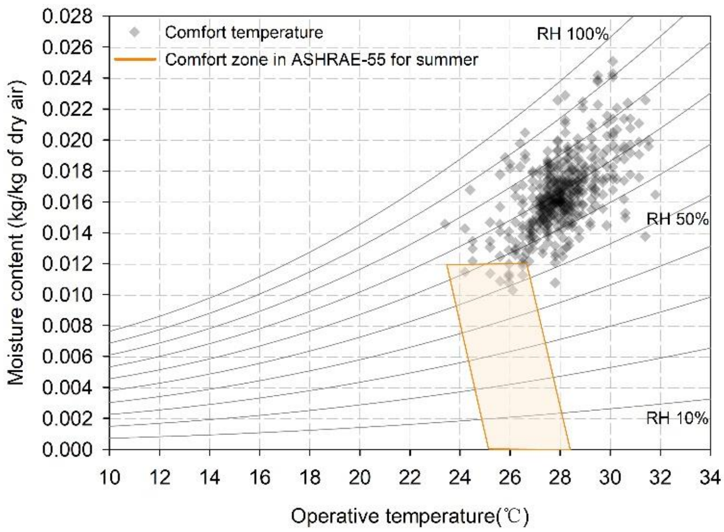


Fig. 4-17. Comparison of comfort temperatures (this study) with recommended comfort zone in ASHRAE-55 (PMV model) for summer.

In order to narrow the deviation between actual sensation votes (TSV) and predicted voting results (PMV), researchers had made unremitting efforts for several generations. In this study, the comparison results among TSV (actual mean votes from questionnaires), PMV (predicted index), ePMV and APMV (predicted adaptive index) was presented in Fig.4-18. By contrasting the TSV with PMV, a relatively large error existed than ePMV and APMV which illustrated that the original model underestimated the occupants' heat tolerance in summer, the higher indoor operative temperature, the larger deviation, and the phenomenon of "scissors difference" was also attested by J. Jiang [35] and Z. Zhang [36]. To further explore the adjustment results, we set the two values as interval limitation: point 1 is the intersection of ePMV (green solid line) and APMV (red solid line) which corresponding the X-coordinate of approximately 27.6℃; the other point is determined by the absolute value of the Y-coordinate difference between TSV and ePMV/APMV, let the intercept as "a" (|YTSV－YePMV|) and "b" (|YTSV－YAPMV|) respectively, when "a" equals to "b" can obtain the point 2 by around 29.8℃ in this research, and hence, three intervals were defined by those two points. When Top was lower than 27.6℃ or higher than 29.8℃, it could be observed that the fitting effects of ePMV was better than APMV by comparing with authentic thermal sensation, and the opposite situation was appeared by Top ranging from 27.6℃ to 29.8℃, which showed a smaller error by APMV. Much less considered but no less important, although the proposed adaptive predicted models could effectively narrow the gap with the actual situation, the accuracy was within a certain operative temperature range, and those results may be vary from each other by different climatic conditions and indoor operating mode. In current study, for the ECS buildings in Urumqi, more appropriate intervals for the usage of adaptive predicted model of APMV and ePMV were gained by 27.6℃ $< T_{op} <$ 29.8℃, $T_{op} <$ 27.6℃/ $T_{op} >$ 29.8℃, respectively.

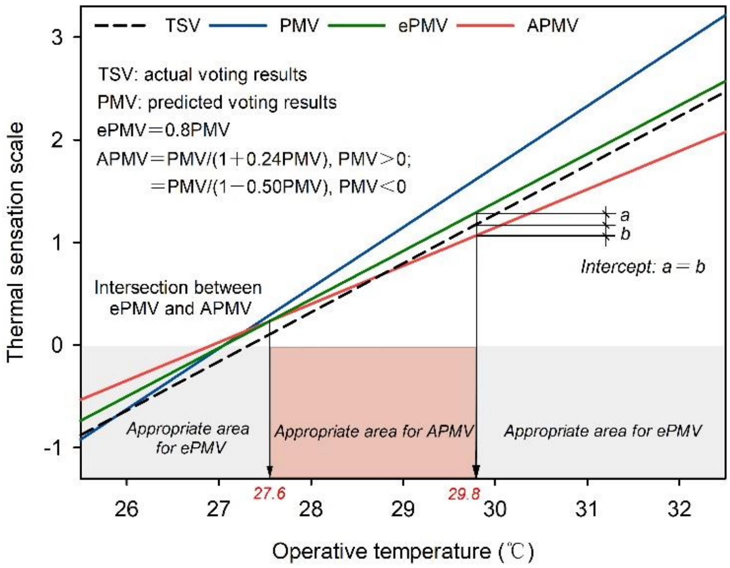


Fig. 4-18. Comparison of TSV (this study) with previous adaptive predicted models.

4.4.2 Energy saving potential in ECS buildings

According to the regression analysis, the neutral temperature in ECS buildings was around 27.9℃. It was higher than the recommended indoor setting temperature 26℃ in the Chinese standard. However, the majority of occupants still felt thermal comfort, which mainly due to the occupants had great freedom of adaption in terms of behavior, physiology and psychology. In addition, the occupants had wide comfort temperature range, with the upper limit of 80% acceptability even exceeding 30℃. As stated above, ECS buildings are common in the dry hot area of China for its convenience and economy. Especially, the summer is very long and hot in Urumqi. Workers spent most of their daytime indoors. Proper indoor temperature is important to maintain thermal comfort, prompt productivity and achieve energy saving in ECS buildings. In current section, we analyzed the energy saving potential of ECS buildings. According to Chinese standard, the outdoor design temperature is 33.5℃ and indoor setting temperature is 26℃ in summer of Urumqi city, and the energy saving potential could be calculated as Eq.4-12.

$$\triangle E = (T_{in} - T_{set}) / (T_w - T_{set}) \qquad (4\text{-}12)$$

where $\triangle E$ is percentage of saved energy, T_{in} is actual indoor temperature, T_{set} is indoor setting temperature and T_w is outdoor design temperature. The calculation results indicated that 15.8% of energy would be saved in ECS buildings in summer.

4.5 Summary

With the conjoint analysis of qualitative (questionnaires) and quantitative (physical measurements) method, this chapter conducted a systematic investigation for public building standard rooms with evaporative cooling systems (ECS) during summer season in Urumqi, China. According to the results of data calculation, the following conclusions can be summarized.

- In ECS buildings during the summer season, the variation of indoor air temperatures were mainly distributed from 26℃ to 30℃ with the relative humidity stayed at a higher level (60%-90%), and the mean air velocity was under 0.2m/s for more than half of the time, which was largely influenced by the outdoor environment.
- Although over 40% of the occupants could accept the current environment, there was still a willingness among them to be slightly cooler, which indicated that the deviation was existed between thermal neutrality and expectation. Through the regression analysis, the expectative temperature (T_e) was 26.6℃, approximately 0.7℃ lower than neutral temperature (T_n) of 27.3℃. The upper limit of 80% acceptable interval for APD was 30.3℃, 1.9℃ higher than that calculated by PPD, which indicted that local occupants had a selective adaptation to the dry-hot climate in Urumqi during summer season.
- Due to the close relationship between comfort temperature and outdoor climatic conditions, an adaptive thermal comfort model was established for ECS buildings in Urumqi based on the coupling effects of subjects' behavioral habits, psychological preference and physiological accommodation. The specific mathematical equation expressed as $T_c = 0.06T_{pma} + 26.17$ (26.8℃

≤ T_{pma} ≤ 38.2℃). In addition, the comfort interval for 90% and 80% acceptable level could be further obtained of 27.1℃－28.9℃ and 26.4℃－30.3℃ respectively.

- PMV had been proved to be not applicable to evaluate the actual thermal sensation in ECS buildings due to its underestimation of subjects' heating tolerance in summer. However, the adjustment PMV model (ePMV and APMV) could be effectively narrow the gap for that deviation. Meanwhile, by quantitating its specific scope of application can receive the optimal usage interval for ePMV and APMV of T_{op}＜27.6℃ / T_{op}＞29.8℃, 27.6℃＜T_{op}＜29.8℃ respectively.
- It was estimated that 15.8% of the cooling energy could be conserved during summer season in ECS buildings, and adaptive comfort zone was recommended to future building design rather than a current constant indoor setting temperature.

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Chapter 5

INVESTIGATION STUDY ON ADAPTIVE THERMAL COMFORT IN EVAPORATIVE COOLING AIR CONDITIONED AND NATURALLY VENTILATED BUILDINGS

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5.1 Introduction

5.1.1 Motivation

Reformation of building technology had inevitably ignore the coupling relationship among energy saving, thermal comfort and environmental protection. For instance, heating, ventilation and air conditioning (HVAC) systems had been largely adopted to guarantee a more comfortable indoor environment since last century. However, it accounts for more than one fifth (20%) of the total building energy utilization throughout the world [1]. Furthermore, based on the refrigerants of chlorofluorocarbons (CFCs), exceeding 40% of the greenhouse gases emission were produced by building sector which posing a great threat to the global environment [2,3]. Although a higher temperature set point was considered as an appropriate strategy to decrease energy demand during cooling period [4], it might sacrifice comfort state to some extent. Therefore, how to pursue the unity of energy conservation and thermal comfort under the background of reducing pollution has become an urgent issue in contemporary society.

Evaporative cooling air conditioned (ECA) system, as a truly sense of passive sustainable cooling technology, had been widely focused in recent years. The operation mechanism of which is based on the distinction between wet and dry bulb air temperature, through the process of liquid-vapor conversion by water (transforming sensible heat to steam enthalpy), thereby resulting the temperature reduction in the system [5,6]. Since the cold source (water) is not only affordable and accessible but also with none of the CFCs utilization, which eliminate the human long-term concern for ozone layer destruction [7]. According to relevant statistics, ECA system has a lower cost of cooling equipment with an initial investment of approximately 50% comparing to the conventional HVAC. Meanwhile, the operating energy consumption is around 20% of normal level, promoting the energy-saving rate achieve to 70%-80% [8,9]. With the possession of high efficiency, economically benefits, energy conservation and environmental friendly, it had been extensive used in the regions that characterized by dry-hot climate in summer such as China, Kazakhstan, Turkey, Iran and other “the Belt and Road” (B＆R) developing countries.

Turpan is located in the northwest of China, according to the climate classification by Köppen-Geiger and Chinese local code, the region affiliated to cold desert (Bwk) and cold zone (CZ), respectively, which commonly described as dry-hot in summer and dry-cold in winter [10,11]. The average outdoor air temperature during cooling period (mid-May to mid-September) is 32.8℃ with the mean relative humidity of 23.2%, and instantaneous daily maximum temperature could even reach 47.5℃ [12]. Such a unique atmosphere is rich in renewable sources (dry-air energy), in other words, the memorably difference between wet and dry bulb air temperature could efficiently drive the operation of ECA, thereby deeming as the most typical and suitable area for this research.

Since the formation mechanism of thermal comfort is the coupling result of behavior, psychological and physiological adaption under the long-term experience (thermal history) [13], both external environment and internal microclimate make a difference on human thermal adaptability. ECA as a new type of working condition, the specific indoor environment and thermal adaption may differ from naturally ventilated (NV) mode. Therefore, it is imperative to explore the discriminative features between ECA and NV buildings, so as to creating a desirable indoor environment that take both the energy saving and environmental protection into account seriously.

5.1.2 Adaptive thermal comfort approach: a short review

M.A. Humphreys [14,15] firstly proposed the concept of adaptive approach and explained that human actual comfort range exceeding the predicted results by PMV model. De Dear et al. [16] based on the 21000 sample data of field studies, established the adaptive model for air-conditioned and naturally ventilated buildings. Through the field investigation of SCATs program, Nicol et al. [17] obtained the control algorithm of the European thermal adaptive model. Furthermore, in Asia [18-20], Australia [21,22] and America [23,24], numerous researchers pointed out that human body is not a passive receiver of the surrounding environment, a variety of adaptability will have a significant impact on thermal comfort, which jointly promote the development of the adaptive theory. Meanwhile, on the basis of worldwide database, this method had been adopted in many international and local codes such as ASHRAE Standard [25], EN 15251 [26] and GB/T 50785 [27] to evaluate the specific working conditions under the complex environment.

China is a vast country with various climatic conditions, life styles and economic levels, which resulting the great differences in human's thermal adaptability [28]. For severe cold zone (SCZ), T. Shao et al. [29] conducted field survey in three different latitudes of northeast China (Harbin, Changchun and Shenyang) to explore the rural residents' adaptive comfort statuses. Analogous study by Z. Wang et al. [30] was presented in Harbin that focus on university classrooms and offices' thermal adaptability. In cold zone (CZ), J. Jiang et al. [31] investigated adaptive thermal comfort in controlled/uncontrolled primary and secondary classrooms at the northwest of China (Shaanxi, Gansu and Qinghai) during winter season and pointed out the upper limit of neutral temperature was 3℃ lower than the recommend minimum value of current standard. B. Cao et al. [32] surveyed air conditioned (AC) university's indoor environment during summer and winter period, the results showed that people with a higher tolerance for different seasons through the long-term thermal experience. In hot summer and cold winter zone (HSCW), Z. Wu et al. [33-35] conducted adaptive comfort pilot studies in naturally ventilated (NV)/split air-conditioned (SAC) dormitories and SAC offices in Changsha, proposed each working condition's acceptable temperature interval based on the investigation results. R. Ming et al. [36] performed thermal adaptive behavior for mixed mode (MM) offices during five time nodes in Chongqing, and indicated the neutral temperature mainly distributed between 23.92℃ to 26.23℃. In hot summer and warm winter zone (HSWW), Y. Zhang et al. [37] and C. Fu et al. [38] by using the field investigation for NV and AC office buildings in Guangzhou, reported that PMV model always significantly overestimate the authentic thermal sensation due to a wider range of adaptions by subjects. And for mild zone (MZ), D. Lai et al. [39] observed actual thermal sensation vote (TSV) of urban residential buildings in Kunming across the whole year could be kept at a relatively stable level comparing to other climates, and approximately 61.71% of the occupants feel neutral due to the stable outdoor environment. Above all, multiply researches were conducted for adaptive comfort under various climates, building types and working conditions, which jointly explained that the coupling effects of surrounding environmental parameters shaped human thermal history, and it will be balanced over a long period of selective adaption.

5.1.3 Scientific Originality

Although Turpan belongs to CZ according to Chinese climatic classification, the zoning index of which is based on the heating/cooling degree day (HDD/CDD). In other words, the extremely dry-hot climate characteristic in summer should not be neglected comparing to cold and long winter period. However, a detailed literature review indicated that few studies of adaptive thermal comfort were proposed in these region during cooling season. Therefore, a further quantitative consideration for different working mode between ECA and NV buildings are essential to establish a more completely database, so as to fill in the blank for this research field.

5.1.4 Target of the work

As afore-mentioned, the main objectives of present research are as following.

- To survey the authentic physical environment and subjective responses for ECA and NV hotel buildings during summer season in Turpan, and determine the neutral and acceptable indoor environment for each operation mode.
- To probe the differences of selective behavior adjustment for ECA and NV condition, and observe its specific effect weight to human comfort status.
- To establish adaptive comfort model that in consideration of the coupling relationships between long-term's psychological and physiological adaption. Meanwhile, verity the accuracy of recommended models in ASHRAE-55 [25], EN 15251 [26] and Chinese GB/T 50785 [27] comparing to actual working conditions.

5.2 Description of experiment proceedings

5.2.1 Target buildings characteristics

The pilot study was unfolded in 3 ECA and 4 NV hotel buildings which were all located at Turpan. For ECA buildings, all cells were equipped with direct evaporative cooling air-conditioned system and operable windows, occupants could by transforming the set point temperature of air-conditioner or open windows (i.e., exhaust damp air out at the high partial pressure of water vapor) to achieve thermal comfort. For NV buildings, none of the mechanical cooling equipment was installed except ceiling fan, and subjects usually adjusted thermal status through changing activity levels, clothing, as well as open windows to enhance indoor air circulation. Therefore, during the investigation, 3 ECA buildings actually belongs to a mixed mode while the other 4 NV buildings were under a free-running condition.

In terms of specific thermal parameters, all surveyed buildings were built at the beginning of 21st century with the construction of steel-framed concrete, due to the similar constructing order of each material layer, the calculated heat transfer coefficient (U-value) of the envelope were basically identical. Among them, exterior walls were composed of aerated concrete panels with U_{wall} approximately by 0.4 W/(m^2.K); floors and roofs were made of concrete slabs with U_{floor} and U_{roof} of 0.3-0.4 W/(m^2.K) and 0.4-0.5 W/(m^2.K) respectively; fenestration were adopt double glazing with a vacuum, possessing the U_{glaze} and solar heat gain coefficient (SHGC) around 1.8-2.1 W/(m^2.K) and 0.4 respectively. The detailed information for aimed buildings are listed in Table 5-1.

Table 5-1. Envelope parameters for investigated buildings.

Mode	Building code	Envelope parameter properties					
		U-floor [W/(m^2.K)]	U-roof [W/(m^2.K)]	U-wall [W/(m^2.K)]	U-glaze [W/(m^2.K)]	[c]WWR	[d]SHGC
[a]ECA	ZFLQ-01	0.4	0.4	0.4	1.8	0.4	0.4
	ZFLQ-02	0.4	0.4	0.4	1.8	0.4	0.4
	ZFLQ-03	0.3	0.5	0.4	2.1	0.4	0.4
[b]NV	ZRTF-01	0.4	0.4	0.4	2.1	0.3	0.4
	ZRTF-02	0.4	0.45	0.4	2.1	0.3	0.4
	ZRTF-03	0.4	0.45	0.4	2.1	0.4	0.4
	ZRTF-04	0.4	0.45	0.4	2.1	0.4	0.4

Note: [a] Evaporative cooling air conditioned; [b] Natural ventilated; [c] Window-to-wall ratio; [d] Solar heat gain coefficient.

5.2.2 Participants

Totally 986 occupants were invited to participate the investigation, it is worthwhile mentioning that the background information revealed 55 were non-local residents. Nevertheless, the preconditions for selective adaptation required a long-term thermal experience, and the results of this part will be in an error to some extent. Hence, we decided to reject that 55 samples for further analysis. In this way, 931 valid datasets were received that contained 446 for ECA group and 485 for NV group. Meanwhile, all selected subjects were guests and staffs who had been living in Turpan for over two years and had adapted to local climatic conditions. Table 5-2 summarized the basic body indexes of the occupants.

Table 5-2. Background information of investigated subjects.

Type	Gender	Number	Age	Height (cm)	Weight (kg)	[a] CI (clo)	[b] BSA (m^2)	[c] BMI (kg/m^2)	[d] MR (met)
ECA	Male	328	32.2 ±4.8 [e]	174.6 ±6.6	70.2 ±9.2	0.30 ±0.12	1.73 ±0.16	22.2 ±2.5	1.1 ±0.10
	Female	118	28.8 ±3.6	162.1 ±5.6	49.8 ±7.6	0.36 ±0.10	1.52 ±0.12	18.8 ±1.8	1.1 ±0.20
	Total	446	31.5 ±4.5	170.5 ±5.4	63.8 ±10.2	0.32 ±0.08	1.68 ±0.13	20.9 ±2.3	1.1 ±0.12
NV	Male	332	29.5 ±3.9	173.4 ±6.3	68.5 ±8.8	0.28 ±0.10	1.70 ±0.15	21.5 ±2.8	1.1 ±0.15
	Female	153	31.2 ±2.8	163.5 ±5.8	51.2 ±6.5	0.34 ±0.12	1.54 ±0.10	19.4 ±2.0	1.1 ±0.20
	Total	485	30.0 ±3.5	169.6 ±7.8	62.5 ±9.3	0.30 ±0.08	1.65 ±0.15	20.6 ±2.6	1.1 ±0.14

Note: [a] Clothing insulation; [b] Body superficial area; [c] Body mass index; [d] Metabolic rate; [e] Standard deviation.

5.2.3 Questionnaire investigation

The subjective questionnaires were distributed to occupants from 12 June to 16 September 2017, during the specific time started at 7:00 am to 20:00 pm for surveyed days. The content was designed in simple and colloquial language which mainly including three modules as below. Module-1 collected fundamental data such as gender, age, height, weight, clothing and activity levels etc., the clothing insulation (clo) and metabolic rate (met) were estimated according to the recommended values in ASHRAE-55 [25] based on the survey results (Table 5-2). Module-2 regarded the occupants' thermal cognitive status, including thermal/humidity/air-velocity sensation vote (TSV/HSV/ASV), thermal/humidity/air-velocity preference vote (TPV/HPV/APV), thermal/humidity/air-velocity acceptability vote (TAV/HAV/AAV) and overall comfort vote (OCV). From which 7-point scale (-3 to 3) was adopted to evaluate sensation and preference vote, and 5-point scale (-2 to 2) was for acceptability and overall comfort vote [25,40], as shown in Table 5-3. Module-3 determined behavior regulation modes to avoid thermal discomfort, including physical adjustments (operating windows, altering ECA set point temperatures, etc.) and auto-adaptive actions (changing clothing and activity levels, etc.).

Table 5-3. Evaluation indicators and scales of the thermal comfort study.

Indicators		Scales						
		(- 3)	(- 2)	(- 1)	(0)	(+ 1)	(+ 2)	(+ 3)
[a]Tem.	[d]TSV	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
	[e]TPV	Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	Warmer	Much warmer
	[f]TAV	--	Clearly unacceptable	Unacceptable	Slightly acceptable	Acceptable	Clearly acceptable	--
[b]RH	[g]HSV	Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid
	[h]HPV	Much dryer	Dryer	Slightly dryer	No change	Slightly wetter	Wetter	Much wetter
	[i]HAV	--	Clearly unacceptable	Unacceptable	Slightly acceptable	Acceptable	Clearly acceptable	--
[c]AV	[j]ASV	Very low	Low	Slightly low	Neutral	Slightly high	High	Very high
	[k]APV	Much lower	Lower	Slightly lower	No change	Slightly higher	Higher	Much higher
	[l]AAV	--	Clearly unacceptable	Unacceptable	Slightly acceptable	Acceptable	Clearly acceptable	--
Over-all	[m]OCV	--	Clearly uncomfortable	Uncomfortable	Slightly comfortable	Comfortable	Clearly comfortable	--

Note: [a] Temperature; [b] Relative humidity; [c] Air velocity; [d/g/j] Thermal/humidity/air-velocity sensation vote; [e/h/k] Thermal/humidity/air-velocity preference vote; [f/i/l] Thermal/humidity/air-velocity acceptability vote; [m] Overall comfort vote.

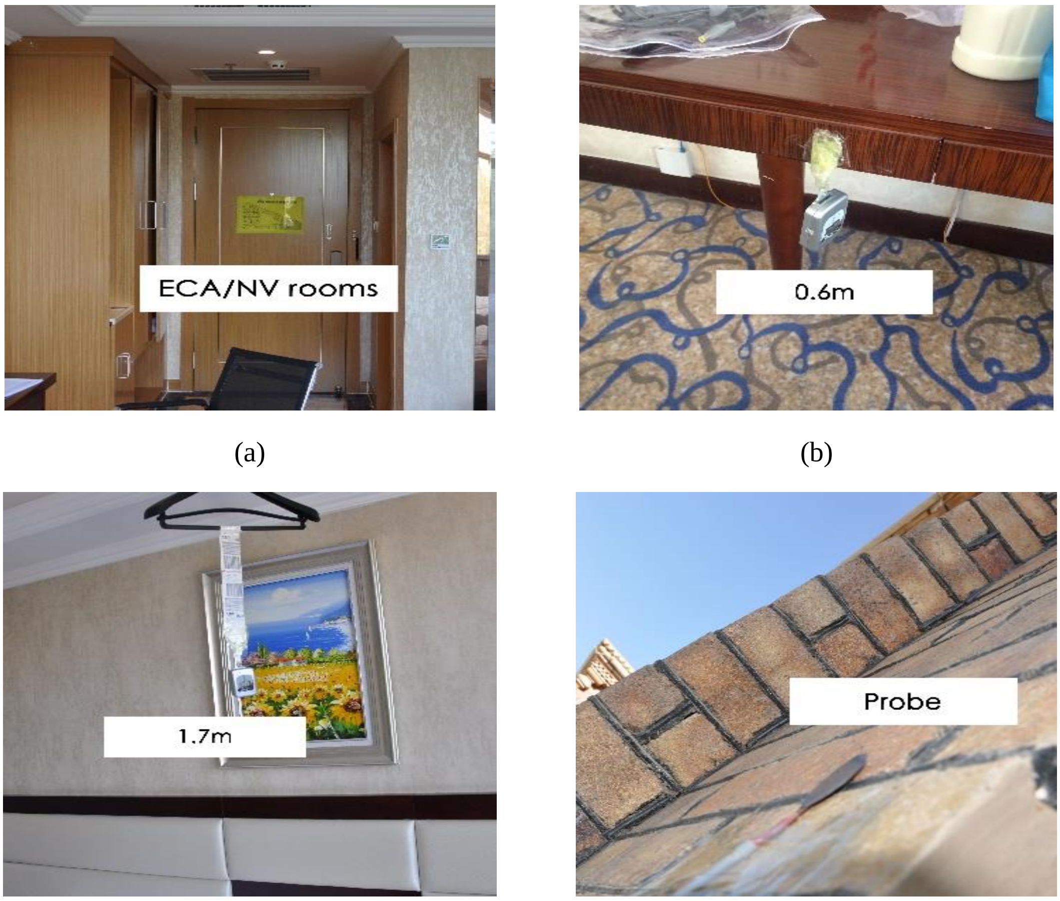
5.2.4 Physical measurements

Physical environmental parameters were measured by calibrated instruments simultaneously with the subjective responses, and the sampling time of equipment was approximately 10 minutes after it became stable. During the investigation, try the best to reduce errors caused by indoor heat disturbance (such as douse the lights and reduce personnel activities etc.). For external parameters, outdoor dry bulb air temperature ($T_{a\text{-}out}$), relative humidity (RH_{out}) and air velocity ($V_{a\text{-}out}$) were tested by local meteorological station at the shading areas among target buildings, and solar radiation intensity (SRI) was received by 8-channel data-logger (DaqPRO-5300) that using a circular probe with a diameter of 10cm attached to the building's façade. For internal indicators, indoor dry bulb air temperature ($T_{a\text{-}in}$) and relative humidity (RH_{in}) were measured by AZ-8828 thermometer recorder at the vertical height of 0.6m (sitting position) and 1.7m (standing position) above the ground, indoor air velocity ($V_{a\text{-}in}$) was determined by Testo 425 anemometer at the same place with $T_{a\text{-}in}$ and RH_{in}, and globe temperature

($T_{g\text{-}in}$) was recorded by adopting a 45mm black sphere at the height of 0.6m with its probe installed in the center of it (WBGT-2010). The detail information of instruments are presented in Table 5-4 and Fig. 5-1, and all the collected data were proposed for further analysis.

Table 5-4. Detail description of measuring instruments and variables.

Instrument	Variables	Range	Accuracy	Reaction time
Thermometer AZ-8828	Dry bulb temperature	-40～85℃	±0.3℃	60s
	Relative humidity	0～99%	±5%	60s
Anemometer Testo 425	Air velocity	0～20m/s	±0.03m/s	≤3s
Thermometer WBGT-2010	Globe temperature	0～80℃	±0.3℃	≤5min
Pyranometer DaqPRO-5300	Solar radiation intensity	0～2000W/m^2	±3%	≤5s



(a) (b) (c) (d)

Fig. 5-1. Physical environmental measurements.

5.3 Results and discussion

5.3.1 Physical environmental parameters

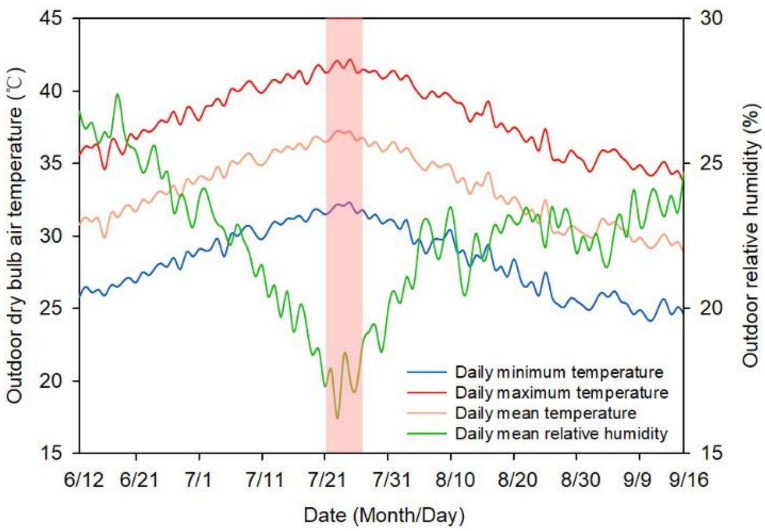
1) Distribution of outdoor environment

In Fig. 5-2, it can be observed that the outdoor air temperature during surveyed period ranged from 24.2℃ to 41.4℃ with the daily mean values exceeding 30℃ for most of the time, and the peak point approximately occurred at 21th July to 25th July. Meanwhile, due to the intense short-wave solar radiation and accompanied by a large amount of evaporation, daily average relative humidity was extremely low that oscillated between 16.3% and 27.5%.

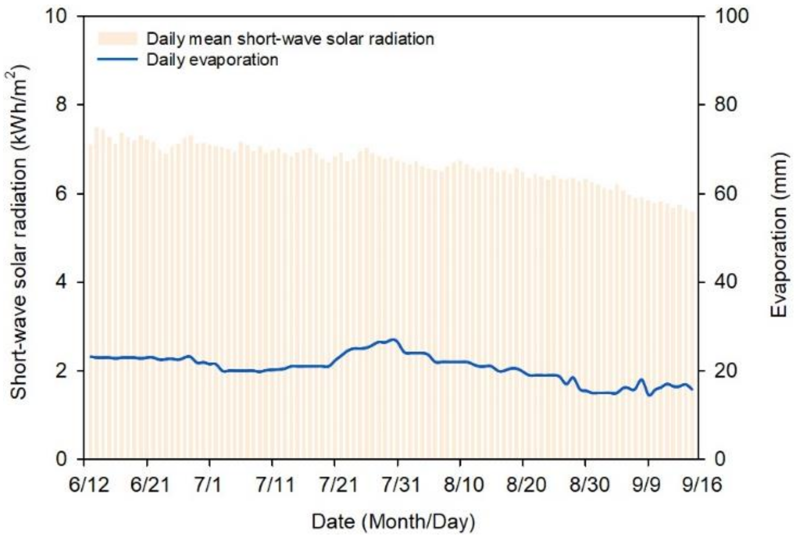
M.A. Humphreys [14] firstly pointed out that the outdoor temperature is a significant index to predict indoor comfort status and established thermal adaptive model. Allowed for time variability in comfort conditions, the prevailing mean outdoor temperature (T_{pma}) was adopted in this study instead of using measured data directly which taken the human thermal history (within 3 days) into account, and the specific algorithm is presented as follows Eq. (5-1).

$$T_{pma\ (today)} = (1-\alpha)\ (T_{od-1} + \alpha T_{od-2} + \alpha 2T_{od-3}) \qquad (5\text{-}1)$$

where $T_{pma\ (today)}$ is prevailing mean outdoor temperature on today (℃); $T_{od-1/od-2/od-3}$ is mean daily outdoor temperature on yesterday/the day before yesterday/3 days ago (℃); α is a constant varying from 0 to 1, which reflects the response degree of continuous mean change for outdoor temperature and assigns the maximum weight to the most similar day (comparing to today), recommended values in ASHRAE-55 [25] varied from 0.6 to 0.9. However, a lower value of 0.6 may be a more reasonable choice for dry-hot climates. Therefore, T_{pma} can be calculated during the investigation course which ranged from 27.4℃ to 39.6℃ with the mean value and standard deviation of 34.4±2.0℃.



(a)



(b)

Fig. 5-2. Outdoor environmental parameters during investigation period: (a) dry bulb air temperature and relative humidity; (b) short-wave solar radiation and evaporation.

2) Distribution of indoor environment

Table 5-5 summarized the distribution of indoor measured data. The mean air temperature with standard deviation in ECA and NV buildings were 29.2±1.8℃ and 32.4±1.3℃, respectively. The average relative humidity in ECA buildings (63.6±10.8%) was double higher than that in NV buildings (32.8±11.2%) which mainly due to the former was accompanied by humidifying effect in cooling process, while the latter was more affected by outdoor environment. The mean air velocity in ECA and NV buildings were 0.15±0.22m/s and 0.29±0.28m/s, respectively, about 80% of the time for both modes were under 0.2m/s that lower than the upper limit specified in ASHRAE-55 [25]. One thing should be pointed out that the statistic results of different vertical heights (0.6m and 1.7m) were nearly identical except for NV buildings' air velocity, the reason is occupants may use ceiling fans to enhance indoor air flow that resulting the higher place with larger values.

For searching a more precisely evaluation indicator, the operative temperature (T_o) was selected in this part for further analysis because it takes both air temperature (T_a) and mean radiant temperature (T_{mrt}) into consideration. Meanwhile, M.A. Humphreys [41] also confirmed that the actual thermal sensation (TSV) was perfectly correlated with T_o. Thus, firstly we calculated the T_{mrt} through T_a , T_g and V_a (based on measured results), and then can obtained T_o via T_a and T_{mrt} of 29.6±1.8℃ for ECA buildings and 32.6±1.5℃ for NV buildings in current research, shown as Table 5-5. The overall process is listed as Eqs. (5-2,5-3) [42].

$$T_{mrt}=[(T_g+273)^4+2.5\times108\times V_a^{0.6}\times(T_g-T_a)]^{0.25}-273 \qquad (5\text{-}2)$$

$$T_o=(T_a+T_{mrt})/2 \qquad (5\text{-}3)$$

where T_{mrt} is mean radiant temperature (℃); T_a is indoor air temperature (℃); T_g is black globe temperature (℃); T_o is operative temperature (℃) and V_a is air speed (m/s).

Table 5-5. Indoor environmental parameters during investigation period.

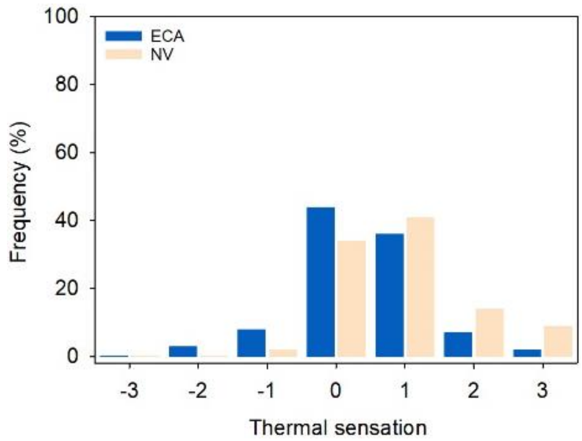
Type	Category	Variables					
		[a]T_a (℃)	[b]RH (%)	[c]V_a (m/s)	[d]T_g (℃)	[e]T_{mrt} (℃)	[f]T_o (℃)
ECA	Mean	29.2±1.8[g]	63.6±10.8	0.15±0.22	29.6±1.8	29.6±1.9	29.6±1.8
	0.6m	29.1±1.8	62.5±10.6	0.12±0.21	--	--	--
	1.7m	29.4±2.0	65.2±11.2	0.16±0.25	--	--	--
NV	Mean	32.4±1.3	32.8±11.2	0.29±0.28	32.5±1.5	32.5±1.4	32.6±1.5
	0.6m	32.4±1.4	33.2±11.8	0.18±0.32	--	--	--
	1.7m	32.6±1.0	30.7±11.5	0.34±0.21	--	--	--

Note: [a] Air temperature; [b] Relative humidity; [c] Air velocity; [d] Globe temperature; [e] Mean radiant temperature; [f] Operative temperature; [g] Standard deviation.

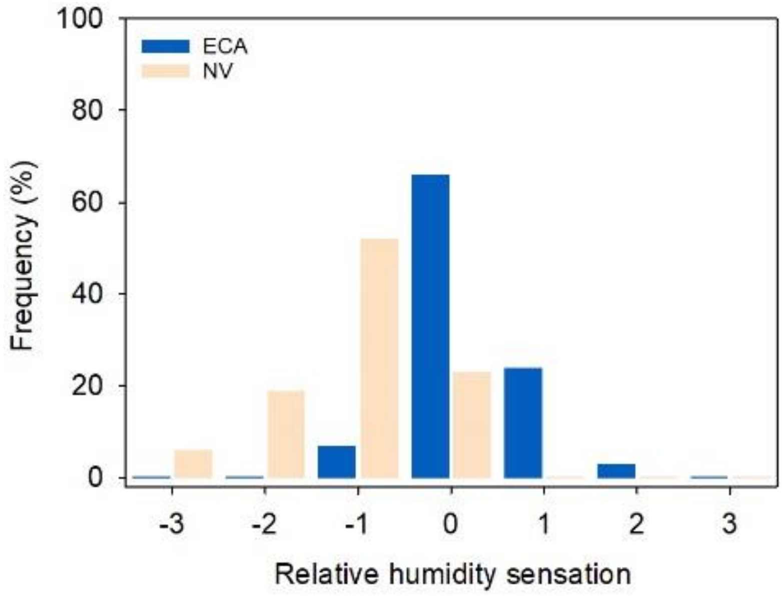
5.3.2 Subjective thermal responses

1) Occupants' sensation, preference and acceptability

The frequency of sensation votes for indoor air temperature, relative humidity and air-velocity in ECA and NV buildings were counted on ASHRAE 7-point scale (Table 5-3), as presented in Fig. 5-3. For ECA buildings, approximately 88% of the occupants voted in the range of ±1 for thermal sensation scales, around 97% and 91% of the total responses lied between ±1 interval for relative humidity and air-velocity sensation scales, respectively. As for NV conditions, about 63% of the votes between 1 and 3 for thermal sensation scale. Meanwhile, the proportion of humidity and air-velocity sensation in -1～-3 range were approximately of 77% and 84%, respectively, which indicated that the majority of subjects felt indoor environment hot, dry and without blowing sensation.



(a)



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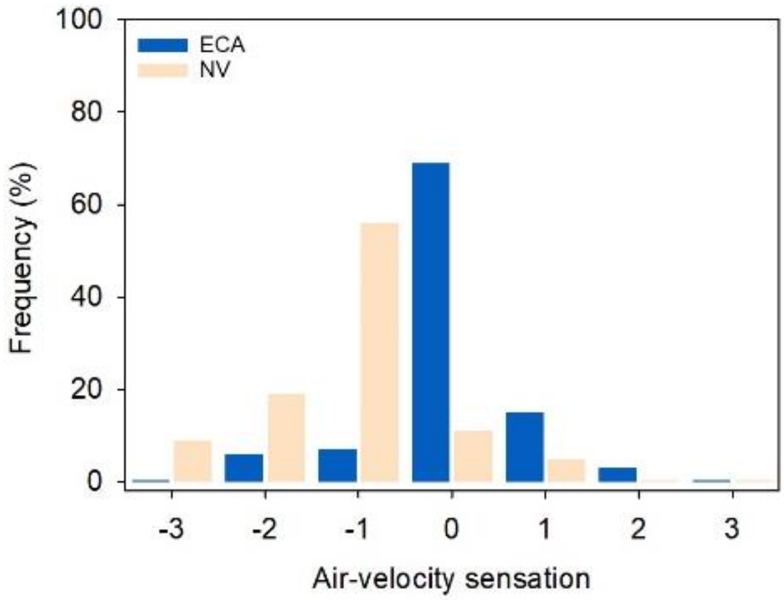
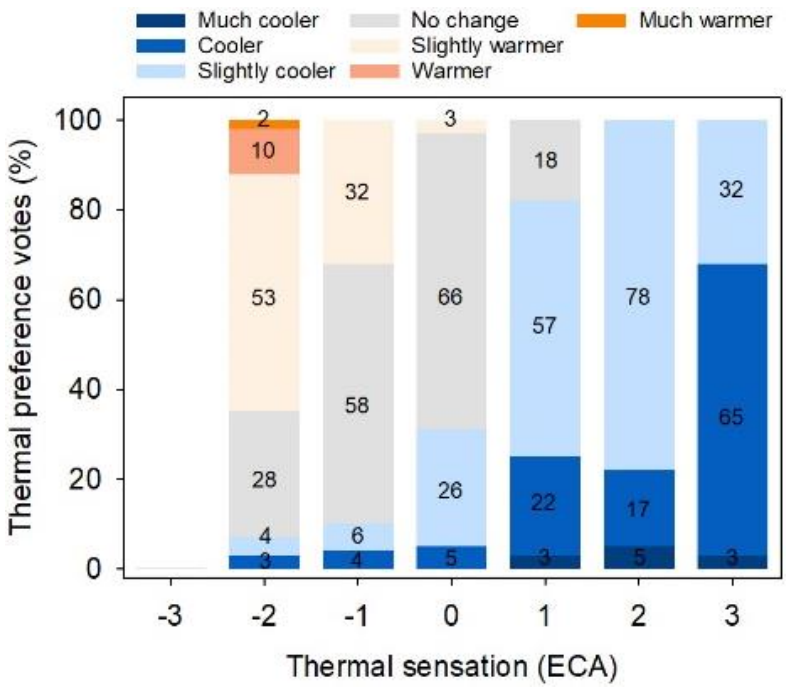


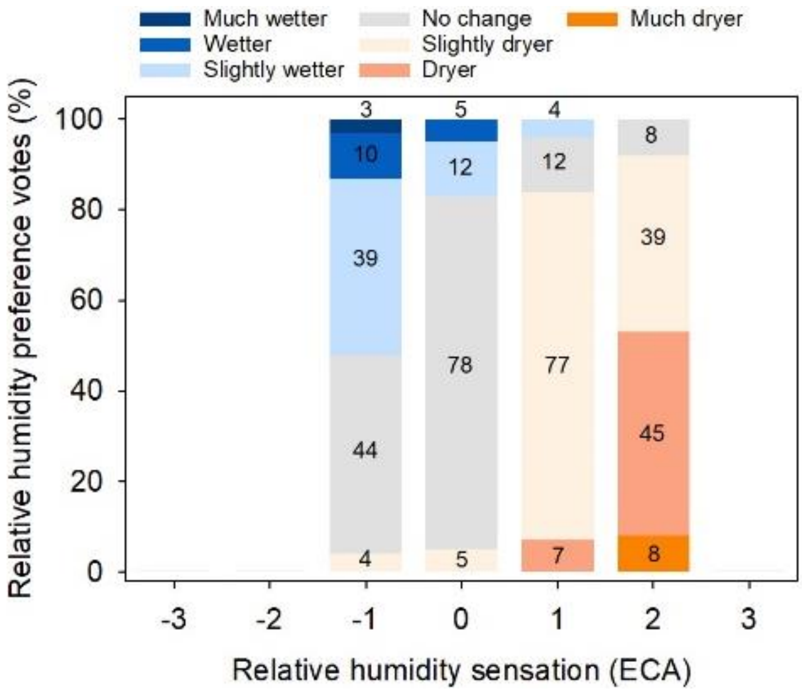
(c)

Fig. 5-3. Subjective responses on 7-point scales: (a) thermal sensation votes; (b) relative humidity sensation votes; (c) air-velocity sensation votes.

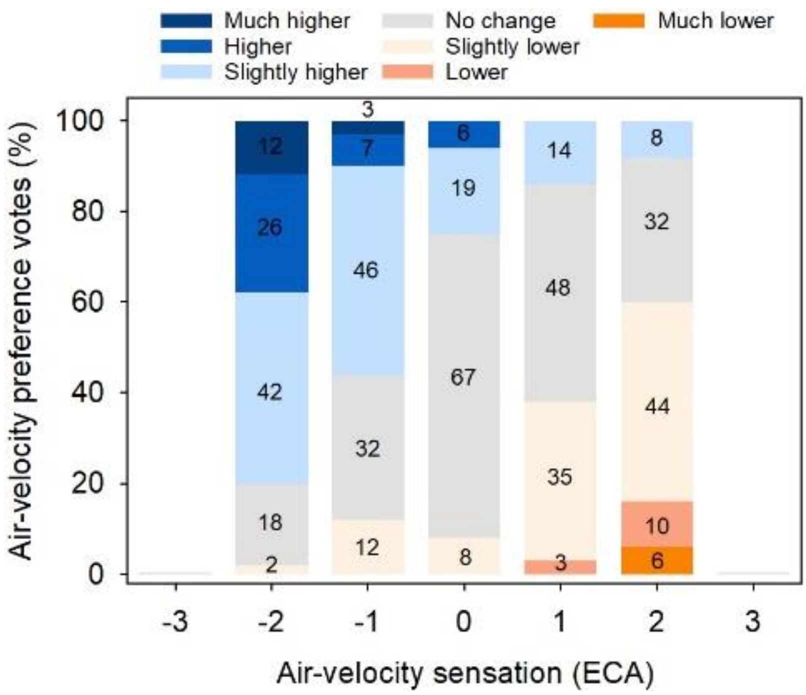
The cross-tabulated summary of sensation compared with preference and acceptability votes for each working mode are shown in Fig. 5-4 and Fig. 5-5. In ECA rooms, it can be observed that, when occupants voted for "slightly cool" (-1) or "cool" (-2) thermal sensation, the preference votes (the sum of "no change", "slightly cooler" and "cooler") were still account for 68% and 35%, respectively. About 54% and 22% of the subjects who voted for this sensation ("slightly cool" and "cool") deemed indoor environment to be “slightly acceptable”, which demonstrated that a bit cooler indoor temperature may be a better choice. Due to the use of ECA was accompanied by air humidification, the willingness of “slightly wetter”/“wetter”/“much wetter” were mainly distributed on the “slightly dry” (-1) humidity sensation scale for approximately 52%, and the voters considered indoor RH “slightly acceptable” and “acceptable” for most of the time. The air speed preference votes were evenly distributed across each air-velocity sensation scale illustrated that the air circulation in such working conditions could basically meet the needs of occupants' comfort status, more than 70% of the occupants in the comfort air-velocity sensation scale (±1) reflected to be “slightly acceptable”, “acceptable” and “clearly acceptable”. In NV buildings, the performance of above three subjective responses was poor. Only 36% of the subjects' thermal sensation votes were located in “neutral” status, out of which 72% preferred indoor temperature to be a litter cooler and approximately 30% voted “unacceptable”. For RH sensation votes, all the results oscillated between 0～-3 scale indicated that the free-running mode causing the indoor humidity maintain a relatively low level, the majority of the occupants preferred wetter indoor environment. More than 75% of votes occurred on “unacceptable” and “clearly unacceptable” when HSV less than 0. Although the mean air-velocity in NV condition (0.29±0.28 m/s) was higher than ECA buildings (0.15±0.22 m/s), the higher temperature and lower humidity still resulting the subjects feel uncomfortable, over 50% of them desired more higher air movements, and surpass 80% of the people voted “unacceptable” and “clearly unacceptable” on the range of -1～-3 air-velocity categories.



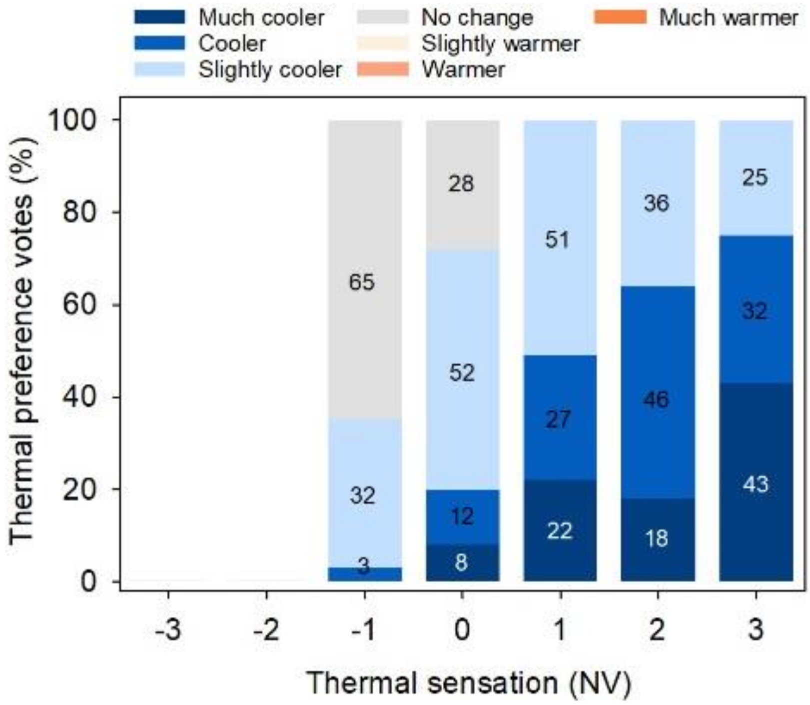
(a)


Much wetter
Wetter
Slightly wetter
No change
Slightly dryer
Dryer
Much dryer
Relative humidity preference votes (%)
Relative humidity sensation (ECA)

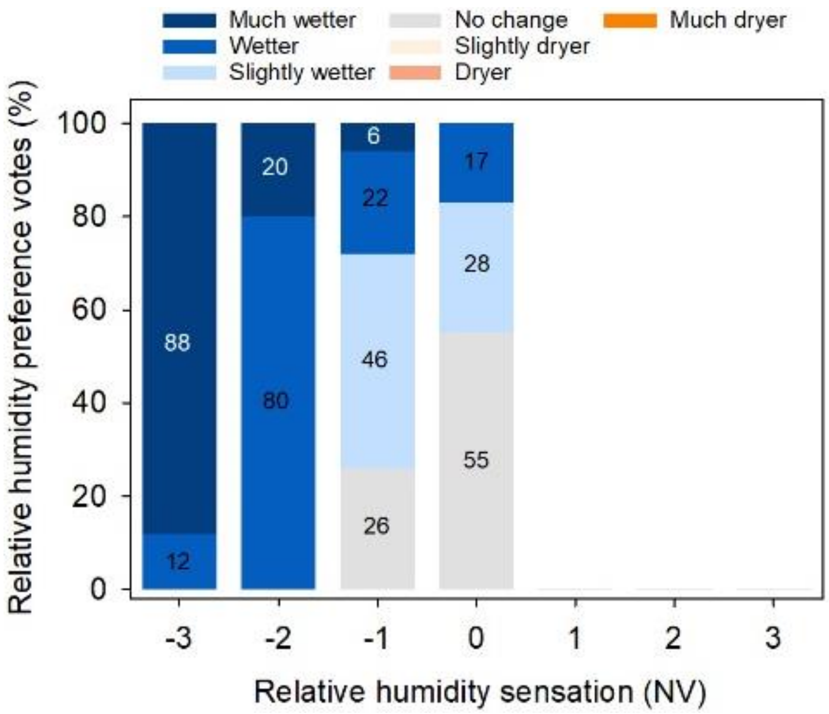
(b)


Much higher
Higher
Slightly higher
No change
Slightly lower
Lower
Much lower
Air-velocity preference votes (%)
Air-velocity sensation (ECA)

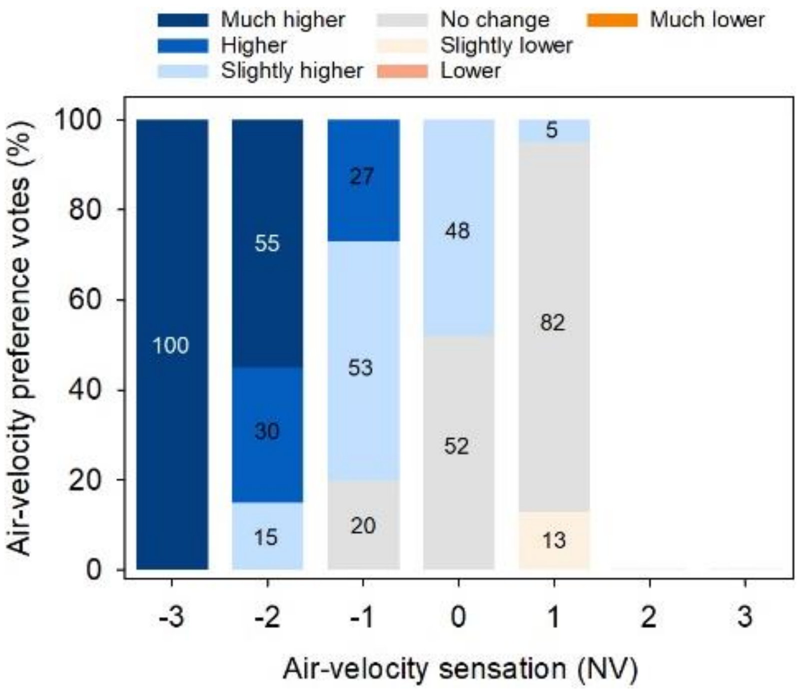
(c)


Much cooler
Cooler
Slightly cooler
No change
Slightly warmer
Warmer
Much warmer
Thermal preference votes (%)
100
80
60
40
20
0
65
32
3
28
52
12
8
51
27
22
36
46
18
25
32
43
-3
-2
-1
0
1
2
3
Thermal sensation (NV)

(d)

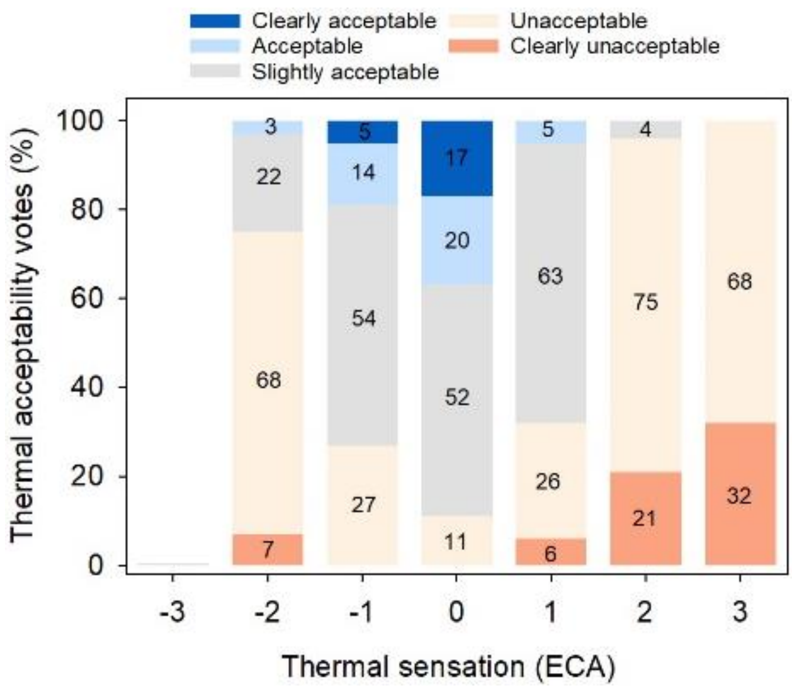

Much wetter
Wetter
Slightly wetter
No change
Slightly dryer
Dryer
Much dryer
Relative humidity preference votes (%)
100
80
60
40
20
0
88
12
20
80
6
22
46
26
17
28
55
-3
-2
-1
0
1
2
3
Relative humidity sensation (NV)

(e)

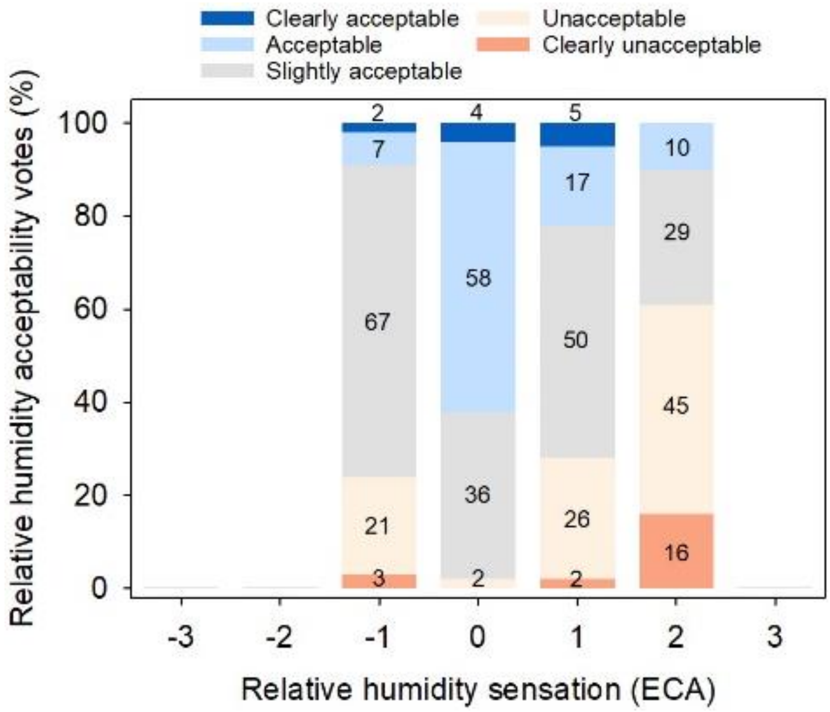


(f)

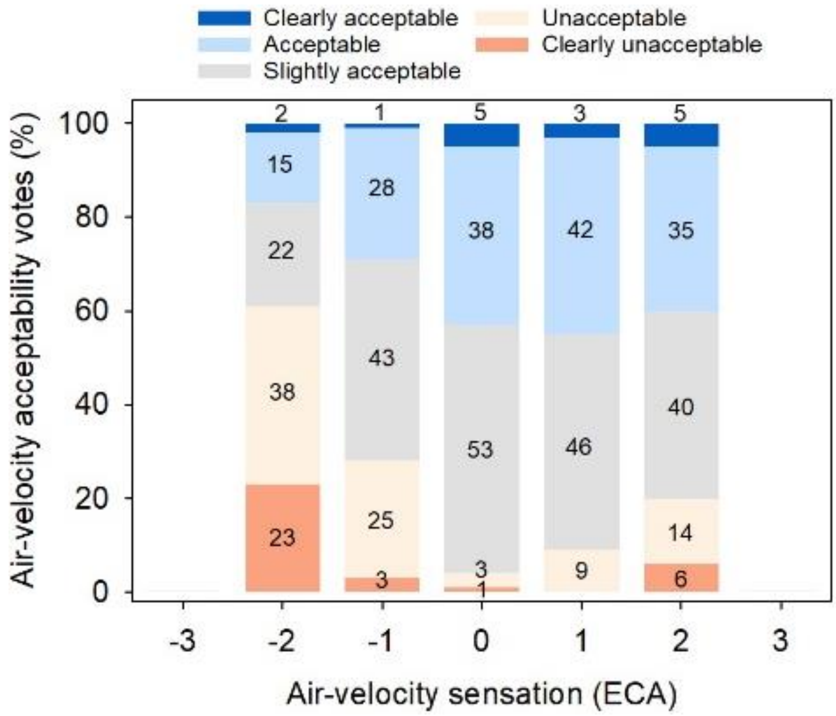
Fig. 5-4. Cross-tabulated summary: thermal sensation and thermal preference votes, relative humidity sensation and relative humidity preference votes, air-velocity sensation and air-velocity preference votes in ECA and NV buildings.



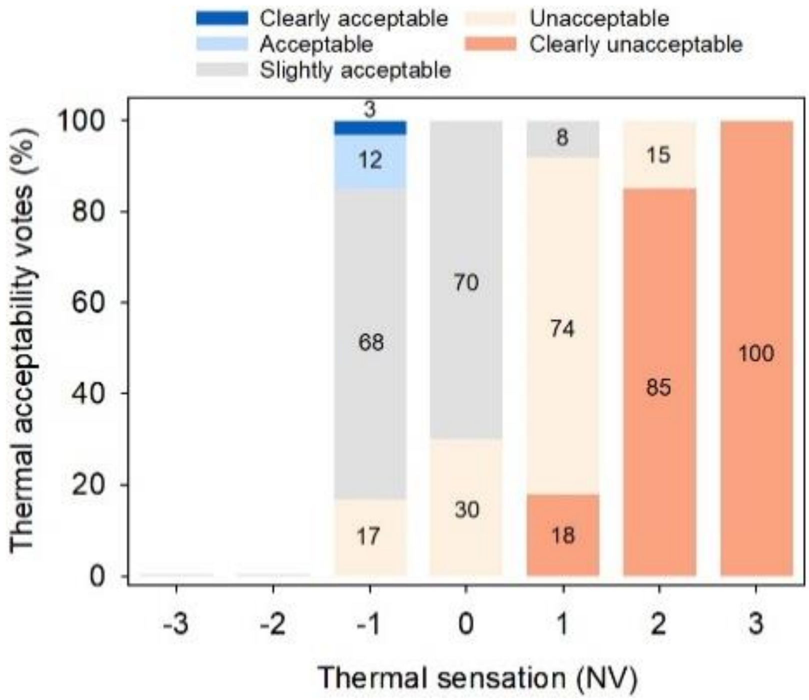
(a)


Clearly acceptable
Acceptable
Slightly acceptable
Unacceptable
Clearly unacceptable
Relative humidity acceptability votes (%)
Relative humidity sensation (ECA)
-3
-2
-1
0
1
2
3
0
20
40
60
80
100

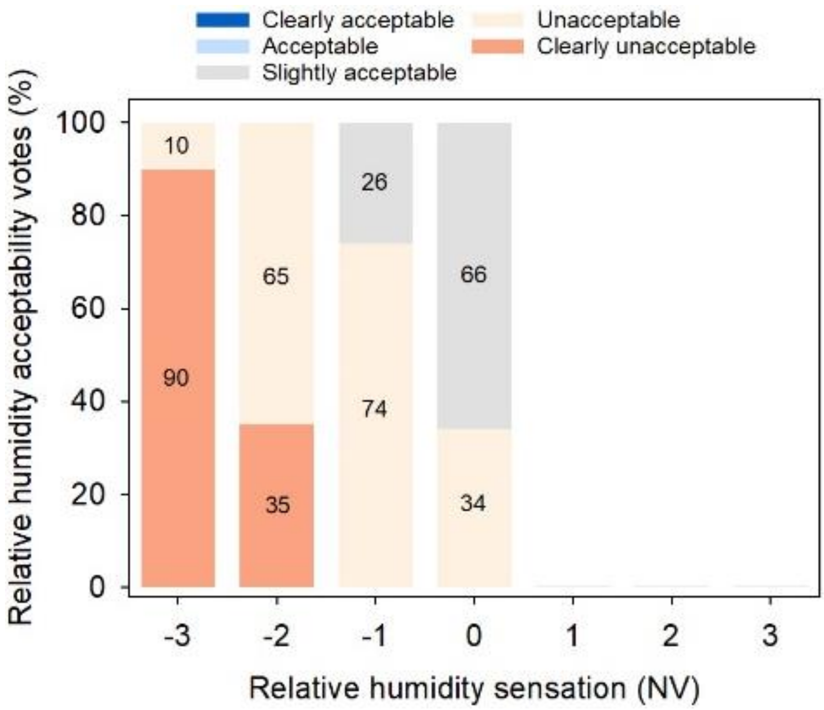
(b)


Clearly acceptable
Acceptable
Slightly acceptable
Unacceptable
Clearly unacceptable
Air-velocity acceptability votes (%)
Air-velocity sensation (ECA)
-3
-2
-1
0
1
2
3
0
20
40
60
80
100

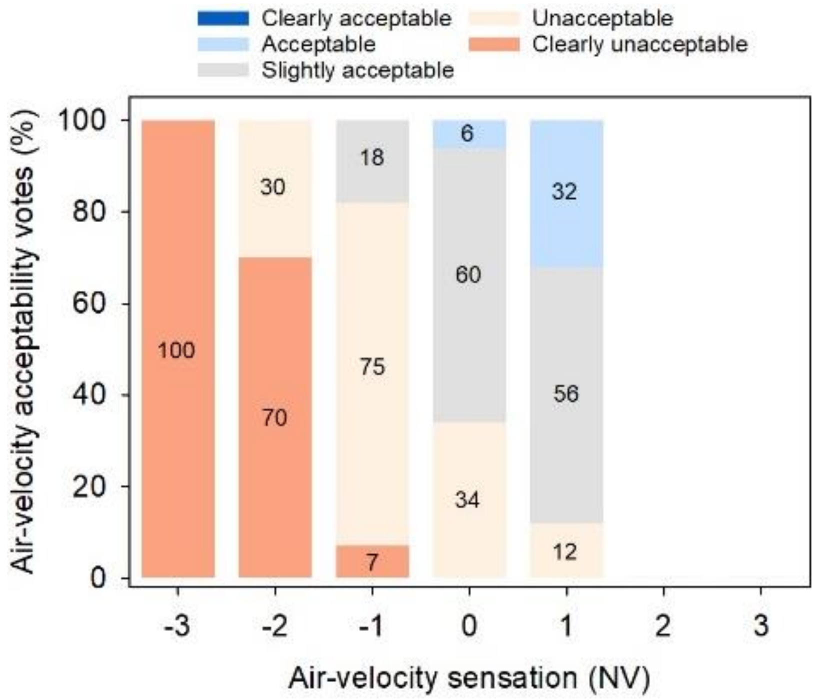
(c)


Clearly acceptable
Acceptable
Slightly acceptable
Unacceptable
Clearly unacceptable
Thermal acceptability votes (%)
100
80
60
40
20
0
3
12
68
17
70
30
8
74
18
15
85
100
-3
-2
-1
0
1
2
3
Thermal sensation (NV)

(d)


Clearly acceptable
Acceptable
Slightly acceptable
Unacceptable
Clearly unacceptable
Relative humidity acceptability votes (%)
100
80
60
40
20
0
10
90
65
35
26
74
66
34
-3
-2
-1
0
1
2
3
Relative humidity sensation (NV)

(e)



(f)

Fig. 5-5. Cross-tabulated summary: thermal sensation and thermal acceptability votes, relative humidity sensation and relative humidity acceptability votes, air-velocity sensation and air-velocity acceptability votes in ECA and NV buildings.

2) Occupants' overall comfort

Occupants' overall comfort votes that considered the coupling effect of indoor temperature, relative humidity and air-velocity were recorded based on 5-point comfort scale, as presented in Fig. 5-6. For ECA group, the majority of subjects (4.6% "clearly comfortable", 42.5% "comfortable" and 34.3% "slightly comfortable") were satisfied with current indoor thermal environment. While the opposing situation was occurred in NV group, approximately 65.7% and 12.4% of the occupants could not accept the indoor environment and voted "uncomfortable" and "clearly uncomfortable", which further revealed that the local specific climate in summer had a significant impact on indoor environment of naturally ventilated buildings.

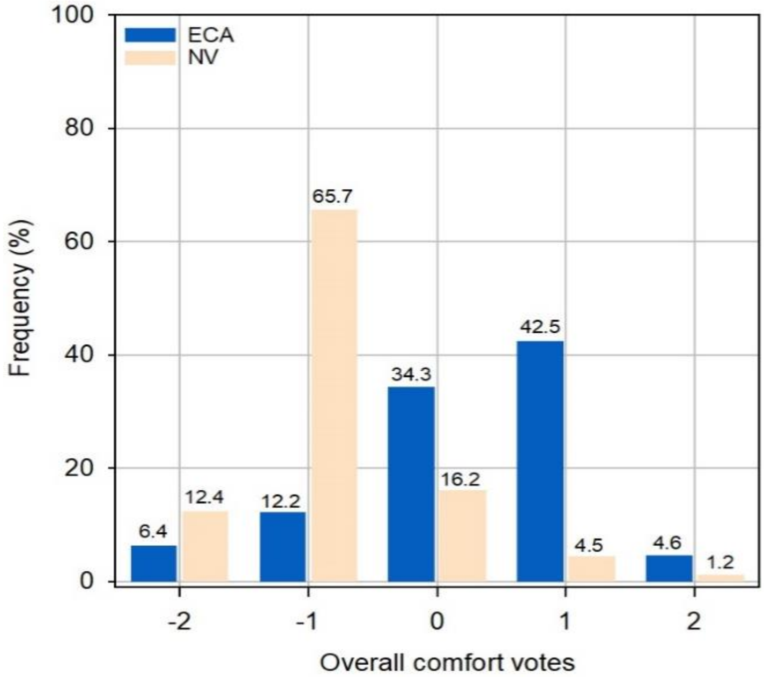


Fig. 5-6. Frequency of overall comfort votes in ECA and NV buildings.

5.3.3 Assessment of various indoor thermal parameters

In this section, linear regression and Griffiths method were conducted between indoor thermal parameters and subjective comfort votes. From which the comfort (neutral) temperature was determined when TSV equals to zero, and acceptable interval of indoor temperature, relative humidity and air velocity were observed at the intersection of the regression line with votes falling on each central three categories (±1).

1) Neutral and acceptable temperature adopting linear regression and Griffiths method

Thermal neutrality described a state that occupants feel neither too cold nor too hot, in other words, it referred to the operative temperature at which the thermal sensation votes of zero. Linear regression method was adopted by numerous researchers to determine the neutral temperature [43,44]. In present study, this method was used to perform the analysis between physical measurements and comfort votes. Fig. 5-7 showed the linear regression relationship between thermal sensation and indoor operative temperature. The regression equations of the ECA group and the NV group were listed as Eqs. (5-4,5-5).

$$\text{ECA: } TSV = 0.47T_o - 13.35 \ (R^2 = 0.29,\ p < 0.001) \qquad (5\text{-}4)$$

$$\text{NV: } TSV = 0.46T_o - 13.36 \ (R^2 = 0.34,\ p < 0.001) \qquad (5\text{-}5)$$

It can be observed that the results of ECA group was significantly different from NV group. Neutral temperature of 28.4℃ was found in ECA group, 0.6℃ lower than that of NV group (29.0℃).

Due to the slope of the two equations were almost the same, which indicated that both groups had the uniform thermal sensitivity to operative temperature. In addition, acceptable temperature range was given by the intersection of the regression line with the “-1” and “1” sensation votes. In this way, two intervals of 26.32℃－30.58℃ and 27.13℃－31.52℃ were obtained for ECA and NV group, respectively. The upper limit of the ECA was 0.94℃ higher than that NV group, which Illustrated that the perennial living conditions had improved the heating resistance of local residents in summer.

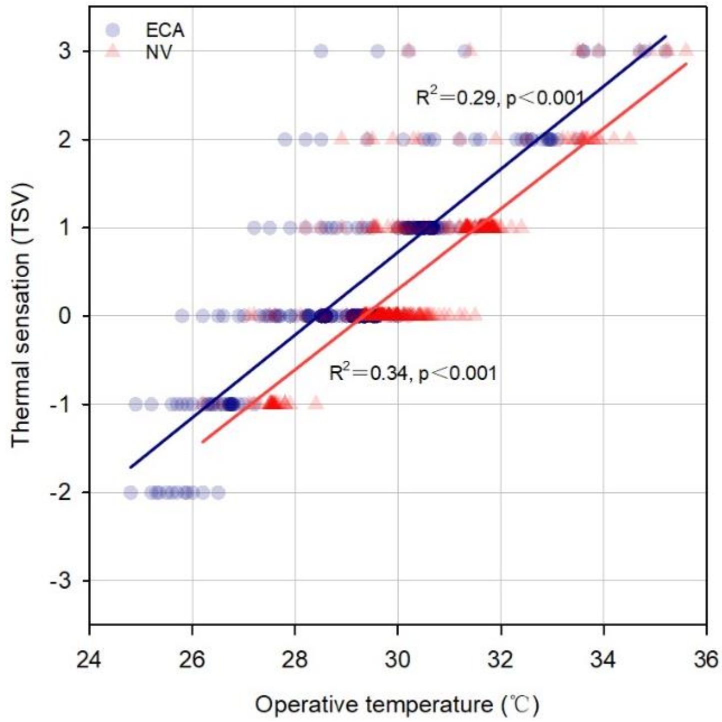


Fig. 5-7. Thermal sensation against operative temperature.

However, some studies revealed that the regression method neglected the occupants' behavior adaptation, so as to reduce the regression coefficient [45,46]. Therefore, this research applied Griffiths constant method to further calculate the indoor comfort temperature in summer for avoiding the errors caused by relatively small sample size based on the algorithm of Eq. (5-6).

$$T_c = T_{o\text{-}mean} + (0 - MTSV)/G \qquad (5\text{-}6)$$

where T_c is comfort temperature (℃); $T_{o\text{-}mean}$ is mean operate temperature (℃); MTSV represents mean thermal sensation vote; and G is Griffiths constant. While adopting Griffiths method, three empirical values of G (0.25, 0.33 and 0.50) had been probed in multiply previous studies [47,48]. The mean comfort temperatures determined by these values were listed in Table 5-6. In current part, the value of 0.33 was adopted for further calculation mainly because there was almost no difference between mean globe temperature (TSV＝0) and mean comfort temperature. In Fig. 5-8, adopting 0.33 as the Griffiths' slope, the mean comfort temperature (ECA: 28.7℃, NV: 30.4℃) was nearly the same as that calculated using regression method (ECA: 28.4℃, NV: 29.0℃).

Table 5-6. Comfort temperature calculated by Griffiths constant method.

Working condition	[a] Tc (℃)	[b] G		
		0.25	0.33	0.5
[c] ECA	Mean	27.3	28.7	29.6
	[e] SD	2.8	2.2	3.0
[d] NV	Mean	28.2	30.4	31.2
	SD	3.8	2.5	2.2

Note: [a] Comfort temperature; [b] Griffiths constant; [c] Evaporative cooling air conditioned; [d] Natural ventilated; [e] Standard deviation.

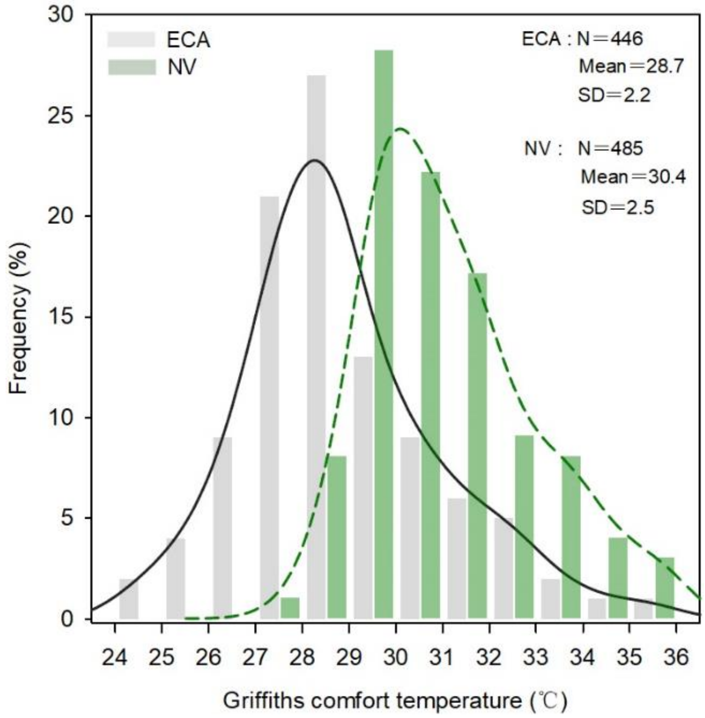


Fig. 5-8. Frequency of Griffiths comfort temperature.

2) Acceptable relative humidity and air-velocity using linear regression

As revealed in Fig. 5-9, by conducting the regression analysis between humidity sensation votes (HSV) and physical humidity measurements, acceptable interval of indoor relative humidity was obtained of 42.5%－76.2% (R^2＝0.31) for ECA group and 35.2%－51.6% (R^2＝0.33) for NV group, respectively. Dhaka [47] and Tewari [48] both reported that the acceptable humidity range for evaporative cooling air-conditioned buildings was oscillated between 35% and 70/80%, and the results in this part was found close to previous researches.

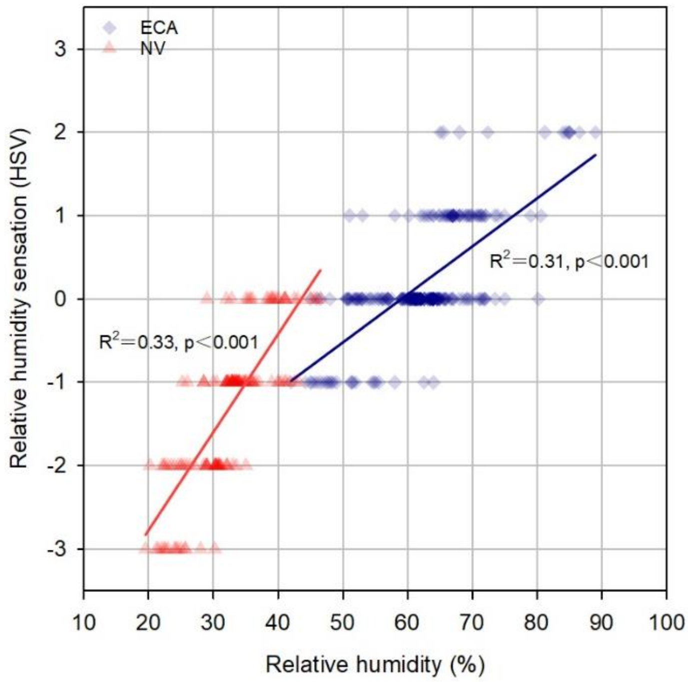


Fig. 5-9. Relative humidity sensation against relative humidity.

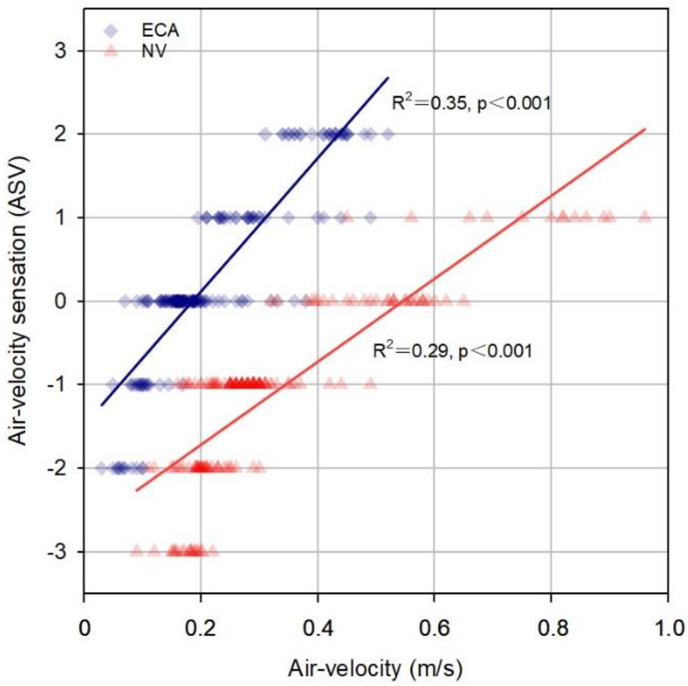
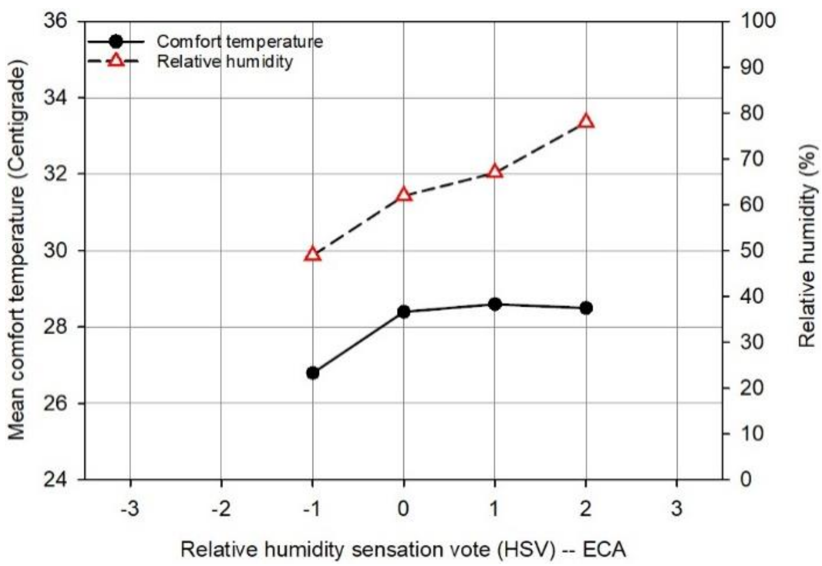


Fig. 5-10. Air-velocity sensation against air-velocity.

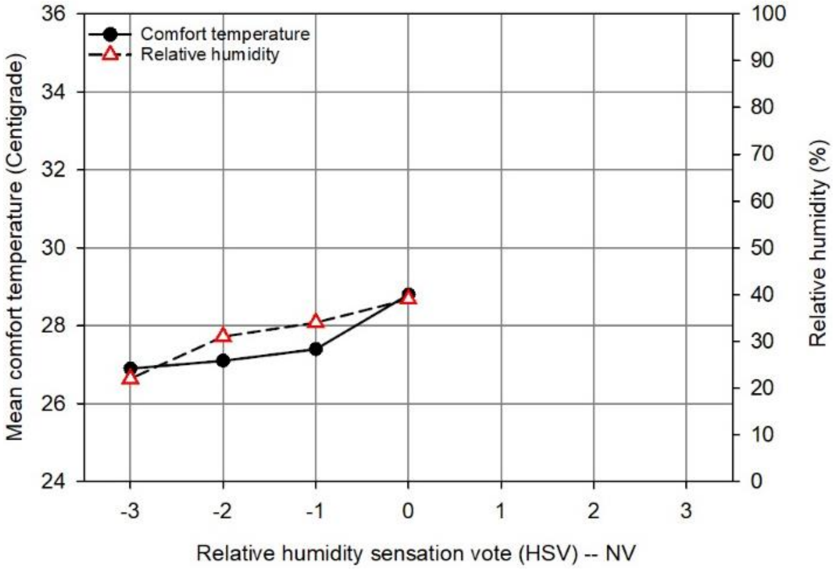
With the same method above, the acceptable range of indoor air velocity was observed for ECA and NV group by 0.06m/s－0.31m/s (R^2＝0.35) and 0.35m/s－0.76m/s (R^2＝0.29), respectively, as shown in Fig. 5-10. Occupants reported the acceptable air movements in ECA group having a mean value of 0.19m/s closest to zero, 0.35 m/s lower than that in NV group (0.54m/s). This also suggested that a moderate increase in air speed could compensate for the discomfort caused by high temperatures. Furthermore, the mean measured indoor air velocity in ECA and NV group (ECA: 0.15 ± 0.22m/s; NV: 0.29 ± 0.28m/s, see Table 5) were found very close to the speed corresponding to '0' air velocity sensation votes (ASV) obtained through linear regression. Kumar [49] deemed 0.62 m/s as the preferred indoor air velocity for the summer season in NV buildings, which including in the scope of the findings for this research.

3) Effect of indoor relative humidity and air velocity on neutral temperature

To probe the influence of indoor relative humidity on neutral (comfort) temperature, we calculated the mean comfort temperature for all humidity sensation categories presented on ASHRAE 7-point scale. Fig. 5-11 shows the comparison of the humidity levels and calculated T_c, taking the humidity sensation votes (HSV) as a reference. It can be observed that the variation trend of T_c and relative humidity is proportional to each other in both mode. This is contrary to the results reported by P. Tewari [48] and L.A. López-Pérez [50], which further indicated that local occupants with a willingness of low temperature and low humidity levels during the long-term experience. In current research, for ECA mode, the highest T_c and RH that can be reached without affecting the thermal comfort standard are 27.5 ± 1.8 °C and 71.2 ± 8.7% respectively; in NV mode, the values transfers to 28.1 ± 2.4 °C and 32.6 ± 6.5%.

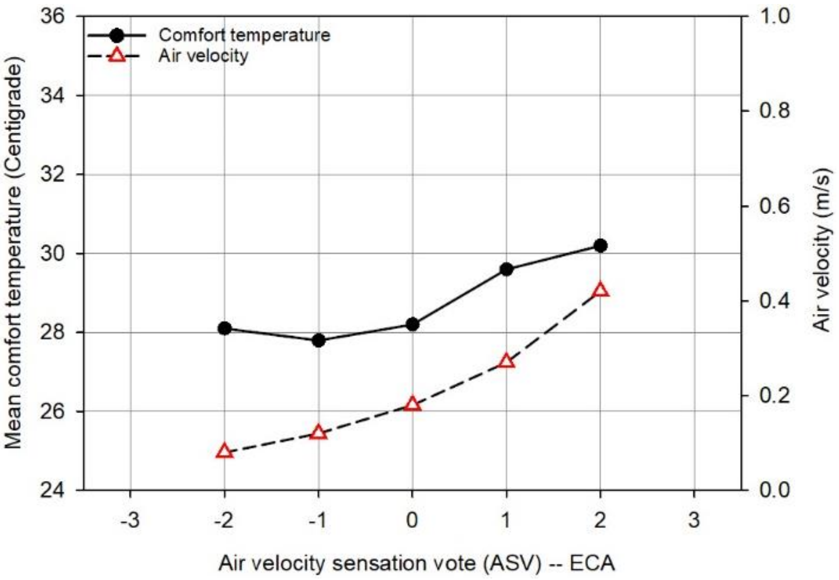


(a)

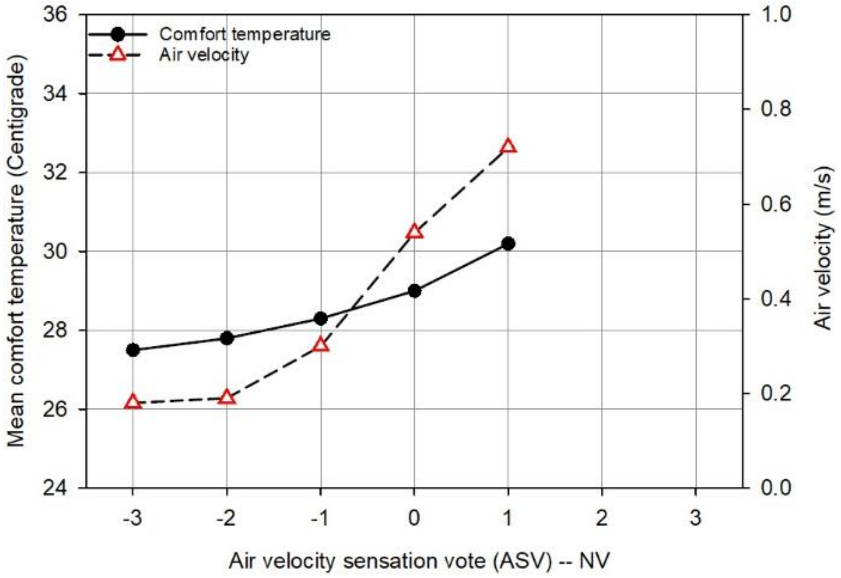


(b)

Fig. 5-11. Relationship between indoor mean comfort temperature and relative humidity sensation vote. (a) ECA mode; (b) NV mode.



(a)



(b)

Fig. 5-12. Relationship between indoor mean comfort temperature and air velocity sensation vote. (a) ECA mode; (b) NV mode.

Fig. 5-12 illustrated the comparison between indoor air speed and comfort temperature adopting the air velocity votes (ASV) as a reference. It can be found that the T_c increased with the air movement goes up. Similar observations were presented by López-Pérez et al. [50] in an investigation study for educational buildings operating in air conditioned (AC) and naturally ventilation (NV) under the hot-humid climate in Tuxtla Gutiérrez-México. In this part, for ECA mode, the highest T_c and V_a that can be obtained without occupants feeling discomfort are 28.5 ± 1.6°C and 0.42 ± 0.12m/s respectively; in NV mode, the values were found to be 29.6 ± 2.5°C and 0.52 ± 0.24m/s.

5.3.4 Assessment of indoor neutral temperature and outdoor environmental temperature: adaptive comfort model

The Fig. 5-13 shows a scatter plot with the linear regression between T_c and T_{pma} in surveyed buildings. And Eq. (5-7) and Eq. (5-8) represent the adaptive comfort model in ECA and NV mode, respectively.

$$\text{ECA: } T_c = 0.08T_{pma} + 25.46 \ (R^2 = 0.32, P < 0.001) \qquad (5\text{-}7)$$

$$\text{NV: } T_c = 0.03T_{pma} + 27.75 \ (R^2 = 0.28, P < 0.001) \qquad (5\text{-}8)$$

where T_c is indoor comfort temperature (°C); T_{pma} is prevailing mean outdoor temperature (°C); R^2 is coefficient of determination. For ECA mode, the mean predicted T_c was 28.5 ± 0.8 °C, with maximum and minimum values of 31.2 and 24.8 °C, respectively. In NV mode, the mean predicted T_c was 29.6

± 1.2 °C, with maximum and minimum of 32.3 and 27.4 °C, respectively.

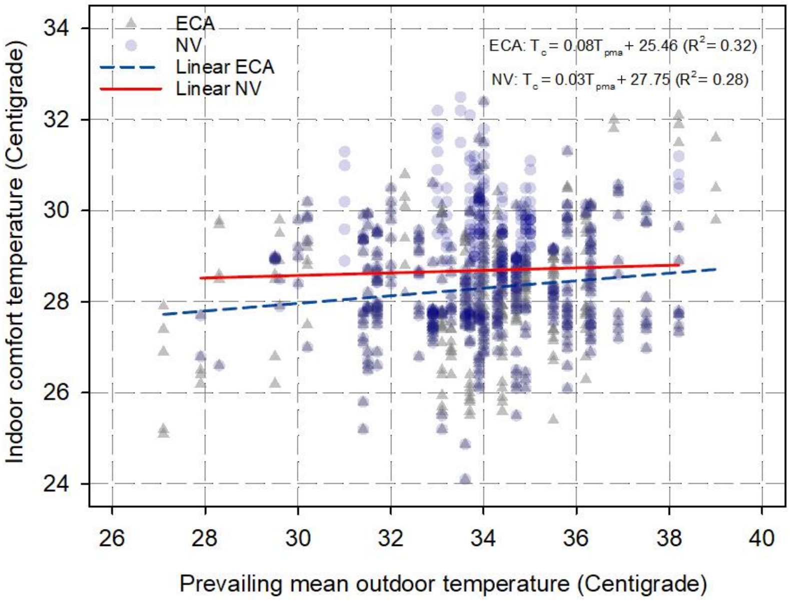
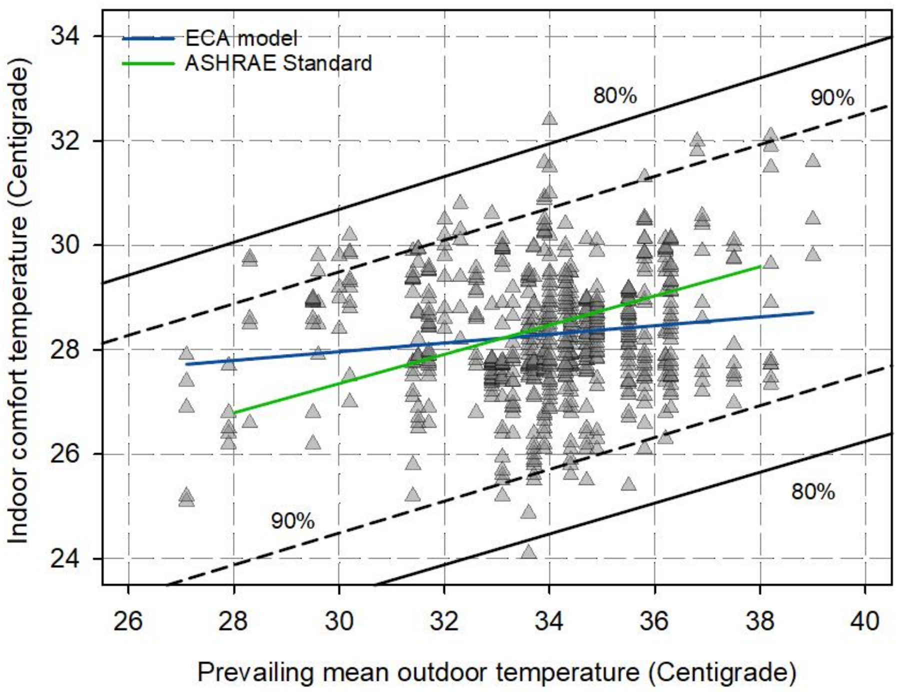


Fig. 5-13. Adaptive thermal comfort model for surveyed buildings with ECA mode and NV mode.

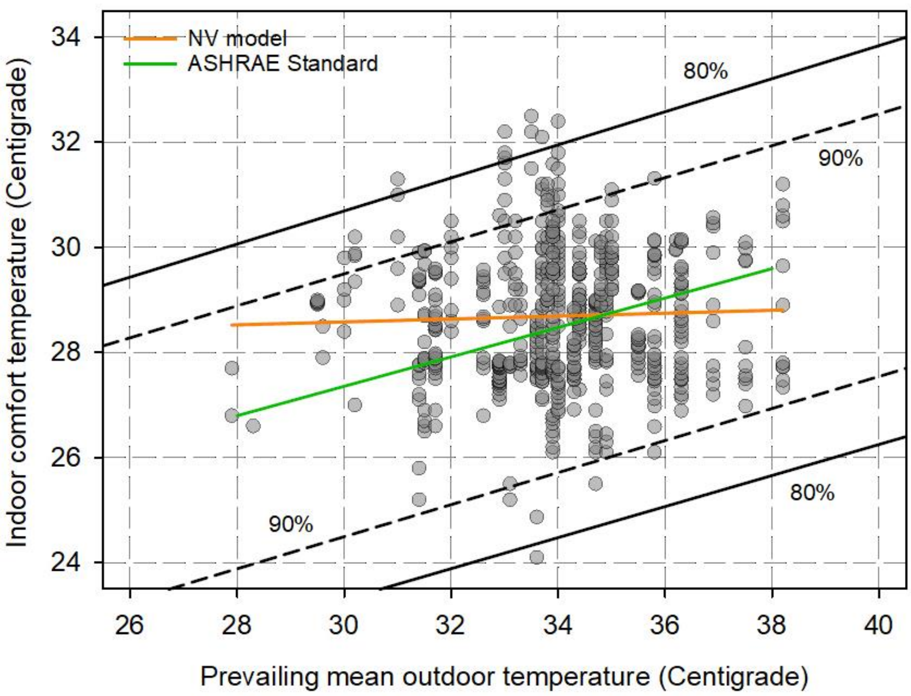
5.3.5 Comparative analysis of adaptive comfort model and existing codes

Fig. 5-14 shows a comparison of the comfort temperature and the comfort zone, using the proposed model, the ASHRAE-55 standard (Fig. 5-14a and Fig. 5-14b), the EN 15251 (Fig. 5-14c) and the GB/T 50785 standard (Fig. 5-14d). The segmented black lines refer the limitation of the comfort zone according to international standards, the green solid line is the international standards and the blue/orange solid lines are actual regression model for different mode.

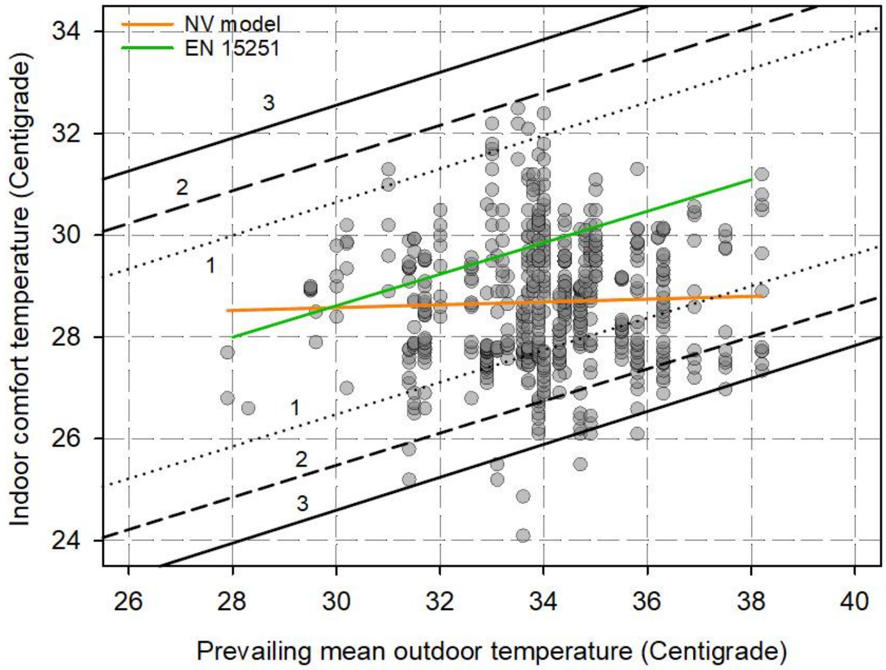
Fig. 5-14a shows a comparison of the T_c as the proposed mode and the ASHRAE-55 standard in ECA mode. From which approximately 88.9% of the sample was within the acceptability level of 90%, the 98.6% within the acceptability level of 80% and the 1.4% was out of comfort zone. As for NV mode, shown as Fig. 5-14b, the proportion mentioned above were 84.6%, 94.5% and 5.5% respectively. In Fig. 5-14c, the comparison of the proposed model and the EN 15251 in NV mode was presented. Considering the acceptability zones of EN 15251 standard, the 94.6% of the sample was within the comfort zone of ± 4K (Level 3), 84.7% within the comfort zone of ± 3K (Level 2) and 71.2% within the comfort zone of ± 2K (Level 1) and the 2.9% was out of the comfort zone. However, in Fig. 5-14d, it can be observed that when comparing the proposed model with Chinese GB/T 50785 standard, few comfort dots were distributed in the recommended comfort zones, which further indicated that China's comfort standards are not tailored to local conditions and ignore the body's long-term adaptations. In other words, if the comfort zone was defined by the current code, it was bound to cause lots of waste of energy consumption.


ECA model
ASHRAE Standard
80%
90%
90%
80%
Indoor comfort temperature (Centigrade)
Prevailing mean outdoor temperature (Centigrade)
34
32
30
28
26
24
26
28
30
32
34
36
38
40

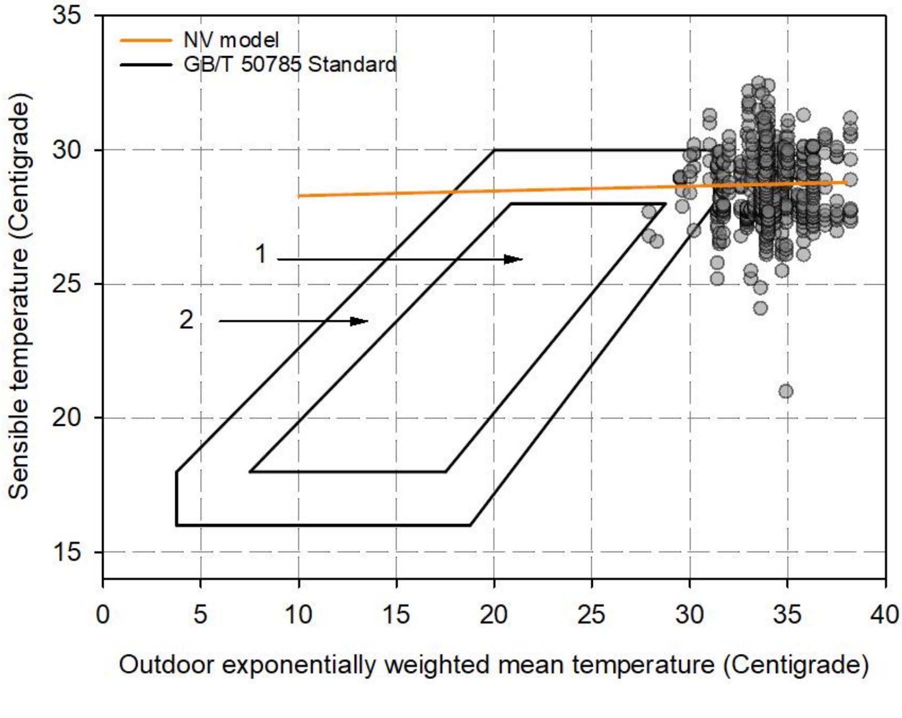
(a)


NV model
ASHRAE Standard
80%
90%
90%
80%
Indoor comfort temperature (Centigrade)
Prevailing mean outdoor temperature (Centigrade)
34
32
30
28
26
24
26
28
30
32
34
36
38
40

(b)



(c)

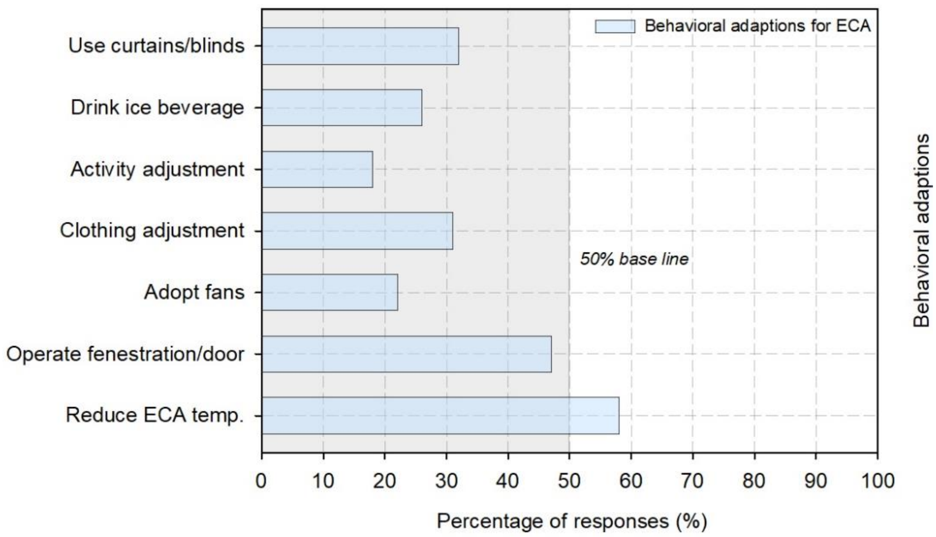


(d)

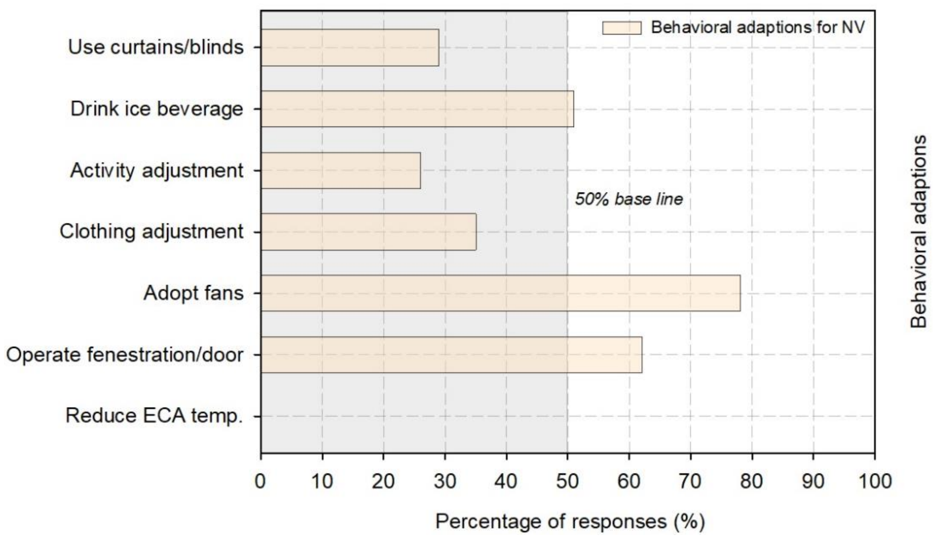
Fig. 5-14. Comparison of the adaptive thermal comfort model with existing standards: a) ECA mode against ASHRAE-55; b) NV mode against ASHRAE-55; c) NV mode against EN15251; d) NV mode against GB/T 50785.

5.3.6 Thermal behavior adjustment

Fig. 5-15 summarized the intent frequency of seven common modes of behavioral regulations when subjects felt hot in summer in both modes. For ECA condition, only reduce ECA temperature surpassed the base line of 50% that around 58%. For NV case, the top three choices that surpassed the base line of 50% were drinking ice beverage, adopting fans and operating fenestration/door with the consequence approximately of 51%, 78% and 62% respectively. Although the use of equipment could satisfy the compensation requirements of thermal comfort, a large amount of energy would be wasted by operating windows/doors at irregular times.



(a)



(b)

Fig. 5-15. The intent frequency of behavioral adaptions for (a) ECA mode and (b) NV mode.

5.4 Summary

With the conjoint analysis above, this chapter conducted a pilot study for public buildings with evaporative cooling air conditioned (ECA) and naturally ventilated (NV) mode during summer season in Turpan, China. According to the data calculation, the following conclusions can be summarized.

- The mean air temperature with standard deviation in ECA and NV buildings were 29.2±1.8℃ and 32.4±1.3℃, respectively. The average relative humidity in ECA buildings (63.6±10.8%) was double higher than that in NV buildings (32.8±11.2%) and the mean air velocity in ECA and NV buildings were 0.15±0.22m/s and 0.29±0.28m/s, respectively.
- For ECA group, the majority of subjects (4.6% “clearly comfortable”, 42.5% “comfortable” and 34.3% “slightly comfortable”) were satisfied with current indoor thermal environment. While the opposing situation was occurred in NV group, approximately 65.7% and 12.4% of the occupants could not accept the indoor environment and voted “uncomfortable” and “clearly uncomfortable”.
- It can be observed that the results of ECA group was significantly different from NV group. Neutral temperature of 28.4℃ was found in ECA group, 0.6℃ lower than that of NV group (29.0℃). Acceptable interval of indoor relative humidity was obtained of 42.5%－76.2% (R^2＝0.31) for ECA group and 35.2%－51.6% (R^2＝0.33) for NV group. The acceptable range of indoor air velocity was observed for ECA and NV group by 0.06m/s－0.31m/s (R^2＝0.35) and 0.35m/s－0.76m/s (R^2＝0.29), respectively.
- For ECA mode, the highest T_c and RH that can be reached without affecting the thermal comfort standard are 27.5 ± 1.8 °C and 71.2 ± 8.7% respectively; in NV mode, the values transfers to 28.1 ± 2.4 °C and 32.6 ± 6.5%. In addition, for ECA mode, the highest T_c and V_a that can be obtained without occupants feeling discomfort are 28.5 ± 1.6°C and 0.42 ± 0.12m/s respectively; in NV mode, the values were found to be 29.6 ± 2.5°C and 0.52 ± 0.24m/s.
- An adaptive thermal comfort model was established for ECA and NV buildings in Turpan based on the coupling effects of subjects' behavioral habits, psychological preference and physiological accommodation. The specific equation expressed as $T_c = 0.08T_{pma} + 25.46$ (R^2＝0.32) for ECA mode and $T_c = 0.03T_{pma} + 27.75$ (R^2＝0.28) for NV mode.
- China's standards (GB/T 50785) is not exactly applicable to Turpan, and this study has improved the basic database for the revision of energy efficiency code.

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Chapter 6

SIMULATION STUDY OF DIFFERENT REGIONS ON ADAPTIVE THERMAL COMFORT

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6.1 Introduction

6.1.1 Motivation

For sake of evaluating the standard of energy utilization, a better view of compromise between upfront investment costs, energy demand, and indoor thermal comfort should be paid enough attention [1]. Building energy demand is influenced by numerous elements, which can be saved to a great extent if the passive technology is considered at the early design stage. Due to the fact that climate conditions vary from the north to the south in China and the climatic adaption makes design parameters more diverse and complex. In addition, building's end-use loads are determined by complex indoor situations, such as the activity level of people, lighting, electrical equipment, and the air infiltration rate [2], and it is also influenced by the outer environment, including solar radiation, air temperature, relative humidity, and wind of heating exchange with the facades [3]. Therefore, the optimization of building envelope plays a significant role on energy conservation. If the envelope parameters are properly chosen at the preliminary design stage, the building energy efficiency can be effectively improved [4]. Thus, the change of building energy demand (heating/cooling/total) under the influence of different parameters has been studied in this chapter.

On the basis of building energy conservation, satisfying the thermal comfort of the human body to a greatest extent is another significant aspect, because it affects occupants' satisfaction, health, and productivity [5]. People spend the majority of their time (about 80%) indoors, it was observed that the working efficiency increased by 15% when they are satisfied with the indoor environment [6]. This study mainly focused on the usage period of office buildings. The adjustment PMV model was selected as the evaluation metrics of thermal condition, and the coupling analysis of energy demand and thermal comfort was performed to explore the optimal passive strategies for the different climate regions in China.

6.1.2 Scientific Originality

The originality of this part lies in the fact that coupling quantifies the relationship between energy utilization and adaptive thermal comfort for urban public buildings that are located in the different Chinese climatic latitudes, and the establishment of multiple benchmark cases with local climatic adaptions breaks the limitation of traditional analyses (which only focus on one model) and also takes the year-round climate change into consideration, which can be deemed as a new research approach for searching the optimization results of this building type. The application of this method could directly calculate the specific energy saving parameters and guarantee the indoor thermal comfort condition at the proper range. Therefore, the simulation results based on the benchmark cases of public buildings in this part could fill the gap of the research to some extent.

6.1.3 Target of the work

The target of this work was to explore the effect of different design parameters on building energy demand (heating/cooling/total) as well as the adaptive thermal comfort. Based on the benchmark cases of urban office buildings, the optimal selection of parameter scheme and energy saving potential are proposed for each climate zone. The findings of this part may provide references on the concept of energy saving for newly built urban public buildings, as well as making a proposal for improving the existing local energy conservation codes.

6.2 Pre-evaluation of climate situations and design parameters

6.2.1 Selection of cities

In order to identify the most important influencing parameters in different climate zones and carry out the simulations, some representative cities have been chosen. From which Changchun from the severe cold zone (SCZ), Beijing from the cold zone (CZ), Shanghai from the hot summer and cold winter zone (HSCW), Haikou from the hot summer and warm winter zone (HSWW) and Kunming from the mild zone (MZ), the locations and geographical data are shown in Fig.6-1 and Table 6-1. Meanwhile, the hourly climate data came from the freely available Energy-Plus weather database [7], and the principles of city selection mainly lie upon three points as following.

- Climate data should be measured in the database of Energy Plus;
- The cities must have typical weather features of each climate zone;
- Weather condition should have a reasonable geographical distribution.

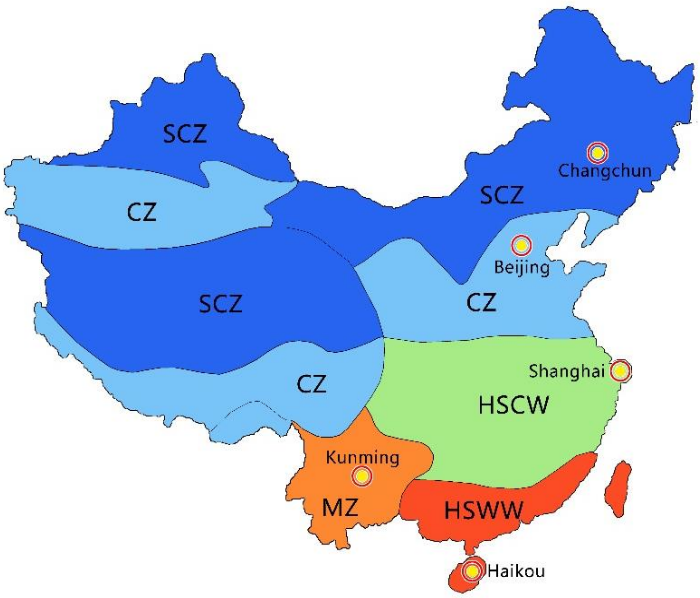


Fig. 6-1. Climate classification and selection of cities.

Table 6-1. Geographical data of selected cities.

Climate zone	Sites	Meteorological Station			$T_{min \cdot m}$ (°C)	$T_{max \cdot m}$ (°C)
		Latitude (°)	Longitude (°)	Elevation (m)		
SCZ	Changchun	125.22	43.90	238	−14.4	23.7
CZ	Beijing	116.28	39.93	55	−2.9	27.1
HSCW	Shanghai	121.43	31.17	3	4.9	28.5
HSWW	Haikou	110.25	20.00	64	18.6	29.1
MZ	Kunming	102.65	25.00	1887	9.4	20.3

6.2.2 Extraction of design parameters

A truly energy-efficient building collects and stores energy by itself and forms a self-circulation system with the surrounding environment, so as to narrow down the energy demand of heating, cooling, lighting, and air-conditioning [8-10]. Through the classification of existing research, which can be divided into two major categories: one is the influence of single/multiple design parameters on building energy consumption (single-objective optimization) and the other is the combined analysis of single/multiple parameters on energy saving potential and adaptive thermal comfort (multi-objective optimization).

For the first aspects, P. Xue et al. [11] researched the influence of window to wall ratio (WWR) with sunshades in low latitude regions of China on energy demand (considering day-lighting requirements), from which they found that comprehensive sunshades had better results than horizontal and vertical ones, and the largest WWR could be designed as 0.55 for south–north buildings and 0.7 for west–east buildings with 1.8 m comprehensive sunshades. A similar study was conducted by Hui Shen et al. [12], which explored the impact of interior roller shades with various glazing properties on energy requirements, as well as pointed out the optimal design strategies for each orientation and location. Also, when the envelope optimization of nearly zero energy demand buildings in north China was analyzed [13], the outcome suggested that the heat transfer coefficient of opaque and transparent envelopes are 0.096 W/(m^2·K) and 0.780 W/(m^2·K), and the solar heat gain coefficient (SHGC) was at least set as 0.474. It is not difficult to find that even the changing of a single parameter will change the energy utilization to some extent. Furthermore, the energy saving potential can also be achieved under the influence of multiple parameters in different climate regions, for example, Susorova et al. [14] investigated the influence of geometry factors on the external transparent envelope (WWR, window orientation, shape factors) energy performance in office buildings to summarize the saving potential in six climate regions of US, which included that the highest energy savings with window geometry (totally 14% overall savings) can be reached in hot climate zones while energy savings in cold and temperate climate zones are marginal. For the different European climate zones, an analysis of optimal WWR and orientation in office buildings and the implications on total energy saving level was conducted in [15], the results indicated that optimal WWR values considering orientation can only be found in a narrow range (0.30 < WWR < 0.45), while, the south-oriented facades in severe cold and severe warm climate zones require WWR values out of this range, and the total energy consumption may decrease by 5%–25% when adopting optimal values. M. Zhao et al. [16] also searched for the energy demand with vital design parameters (WWR, SHGC, shape factors, etc.) in different Chinese climate regions and the results showed that the improvement of the sensitive design parameters for each climate region resulted in the maximum total energy demand reductions below: 75kWh/(m^2·a) in SCZ, 40kWh/(m^2·a) in CZ and HSCW, 50kWh/(m^2·a) in HSWW, and 35kWh/(m^2·a) in MZ. Although these studies were for residential buildings, the method is still adaptable to other types of buildings.

For other aspects, the multi-objective analysis of energy consumption and comfort adaption has been carried out by multiple researchers in recent years, and since heating, ventilation, and air conditioning (HVAC) systems account for most of the building's energy consumption, the parameters of these are extracted for evaluating the thermal comfort. Z. Wu et al. [17] focused on 11 split air-conditioned office buildings to study the applicability of thermal comfort standards and determine the energy efficiency by comparing with the predicted mean vote - predicted percentage dissatisfied (PPV-PPD)—95% of occupants were satisfied with the adjusted model while 8.6% of cooling demand could be saved during the summer period. A parallel study by Jasmin Anika Gartner et al. [18] was also conducted with the consideration of thermal comfort and energy saving potential by comparing three HVAC systems (mechanical ventilation, radiant ceiling, and thermally active systems). Their studies both indicated that various HVAC design parameters played a significant role for energy efficiency as well as thermal adaption. R. Ming [19] and Daniel Sanchez-Garcia [20] placed emphasis on the need for a time dimension that would take the seasonal replacement node (latter spring, early/middle/latter cooling period, early autumn) and climate change (2020, 2050, 2080) into account as they all believed that changes in time or season have an impact on body adaptability and behavioral energy saving. Furthermore, the multi-objective analysis of energy demand, thermal comfort, and cost that focused on a single parameter (building envelop) had been studied by R. Wang [21] by comparing it with the base-case building to getting the optimal value range of the target parameter.

Above all, according to the previous literature review, there is no doubt that the design parameters have a significant role on building energy demand as well as indoor thermal comfort. However, numerous researchers' optimization processes were based on a limited number of parameter variations and neglected the correlation of factors themselves, which may have led to the one-sidedness of the results. Therefore, a more detailed interval division of metrics was carried out in this part. Table 6-2 is considered to show the different influence levels of parameters in various climate regions of China, there were, in total, six parameters extracted from the literature above, which were identified as the most significant factors to this study, and the specific parameter optimization scheme is introduced in the following part.

Table 6-2. Priority level of design parameters.

Design parameters	Climate zones/Cities				
	SCZ	CZ	HSCW	HSWW	MZ
	Changchun	Beijing	Shanghai	Haikou	Kunming
Orientation [--]	●	●	○	○	○
Layer of EPS insulation [m]	●	●	●	●	●
U-value of fenestration [$W/(m^2·K)$]	●	●	●	●	●
SHGC [--]	○	○	○	●	●
WWR [--]	●	●	○	○	○
Infiltration rate [h^{-1}]	●	●	●	○	●

Notes: ● represents the most sensitive design parameters, and ○ is the subdominant design parameters.

6.3 Simulation studies and workflow

For evaluating the influence level of parameters on energy demand as well as indoor thermal comfort, the benchmark and adjusted cases for each climate region were established in Open Studio Sketch-Up plug-in. Meanwhile, using the engine of Energy-Plus (EP-Launch) to calculate the instrument definition file (IDF) files, respectively. The benchmark cases adopted the Chinese design standard for energy efficiency of public buildings, and the energy demand of benchmark cases provided the comparative prototype for other cases with optimization.

6.3.1 Mathematical model and assessment criteria

1) Energy consumption model

In numerical simulation processes, the thermal balance method is adopted for calculating the end-use energy demand and total annual loads. The core of this method is that heat is transferred between different systems until the energy states are the same, and the law of conservation of energy is followed throughout the heat exchange process. In this study, the energy loads algorithm in Energy-Plus was based on Eq.6-1, and the basic assumption was that the room air temperature was uniform as well as the temperature of building envelope surfaces [22]. By calculating the heat transfer of the envelope under the heat disturbance at each time step, the thermal performance of the whole building can be calculated, such as the heating/cooling loads and indoor air temperature.

$$\sum C_b \varepsilon_{ik} \psi_{ik} \{[t_k (n) /100]^4 - [t_i (n) /100)^4]\} + q_i (n) + q_i^{\,r} (n) + \omega_i^{\,c} [t_r (n) - t_i (n)] = 0 \qquad (6\text{-}1)$$

where C_b ($W/m^2 \cdot °C$) is the black sphere radiation constant, which equals 5.68; ε_{ik} is the blackening between the internal surface i and k; ψ_{ik} is the radiation angle of internal surface from i to k; t_i (n) (°C) and t_k (n) (°C) are internal surface temperatures; q_i (n) (W/m^2) is the heat flux gained from the internal surface i; $q_i^{\,r}$ (n) is the solar heat gained of the internal surface i; $\omega_i^{\,c}$ (W/m^2 °C) is the convective heat transfer coefficient of the internal surface; t_r (n) (°C) is the indoor air temperature.

Due to the fact that the building exterior envelopes (outer wall and roof) are always in contact with the outside environment, the envelope heat transfer is a three-dimensional unsteady process. Thus, the most crucial issue is to solve the rule of temperature and heat flow field changing with time. In this study's simulation process, the new solution contained elements that are called conduction transfer functions (CTFs), which are used to calculate the unsteady heat transfer of the building envelope [23]. The thermal characteristic of the building is separated from the external disturbance and the response coefficient is considered to be the thermal characteristic of the envelope itself, as long as the reaction coefficient of the building and instantaneous/historical values of the disturbance are known, it can calculate the heat flow at that time.

There is no doubt that most of the energy exchange between inside and outside of the building during the day comes from the solar radiation, which mainly contains direct solar radiation and diffuse radiation. Although the error in calculating the total solar radiation under clear sky conditions is minimal, it cannot be ignored that there are a lot of overcast conditions throughout the year. In other words, diffuse radiation is also an important problem because there exists a lot of cloud cover in such conditions, which has a significant correlation with the sum of solar radiation. Therefore, the solar radiation model, which considers both cloud cover and temperature difference, was adopted in this study and the algorithm is based on Eq.6-2 [24]:

$$G = G_0 \left[a\sqrt{(T_{max} - T_{min})} + b\sqrt{(1 - C/8)}\right] + C \qquad (6\text{-}2)$$

where G (MJ/m^2) is the total daily radiation; G_0 (MJ/m^2) is the total daily astronomical radiation; a, b represent empirical coefficients, which equal 0.75 and 1.23, respectively; T_{max} (°C) is atmospheric maximum temperature; T_{min} (°C) is atmospheric minimum temperature; and C (%) is total cloud cover.

2) Thermal comfort model

The indoor thermal environment directly affects the body comfort. The coupling relationship among air temperature, relative humidity, mean radiation temperature, and air speed should be comprehensively analyzed instead of considering a specific indicator. ISO 7730 recommended taking the equations of predicted mean vote and predicted percentage dissatisfied (PMV-PPD), which was founded by P.O. Fanger, to evaluate the thermal comfort index [25]. However, considered the body's thermal adaptability, the APMV model was adopted to conduct further simulation and the specific value of adaptive coefficient (λ) and evaluation criteria were introduced in chapter 2.

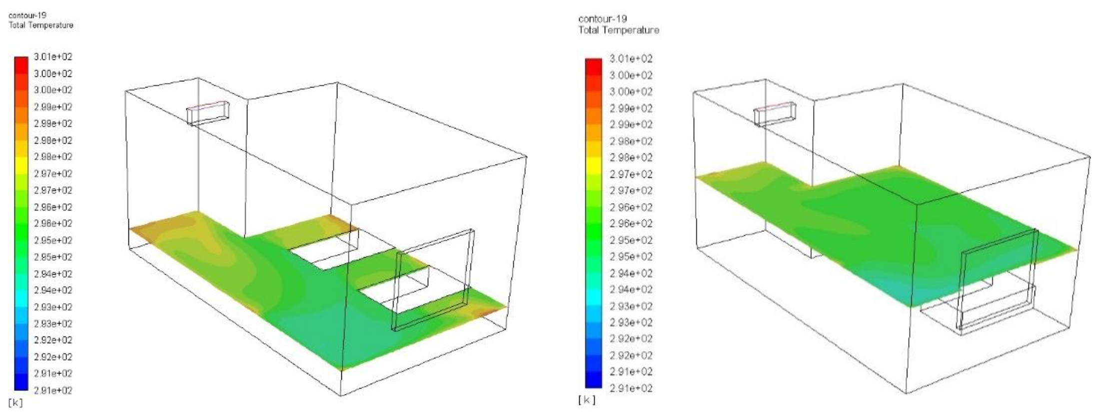
6.3.2 Basic simulation assumptions

Several appropriate assumptions were made in order to simplify the simulation process (accelerate calculation speed) as well as reduce the errors from the results, which mainly lie upon four points as following.

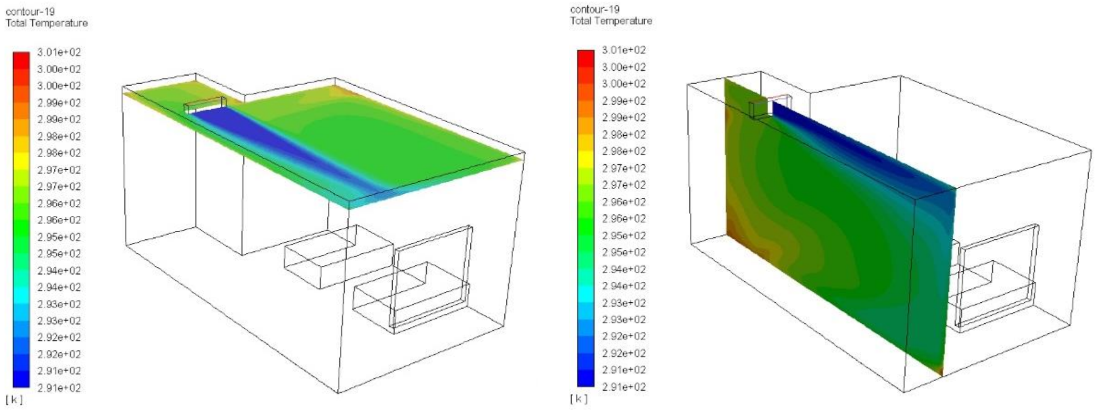
- The rooms with similar functions in the building's geometrical model were merged into the same thermal zone (i.e. thermal zone 1: office cell; thermal zone 2: meeting space; thermal zone 3: equipment room);
- The inner walls (three surfaces), floor, and inner ceiling are adiabatic—heat transfers between the room and outside environment only through the exterior wall with fenestration;
- Direct solar radiation is mainly absorbed by the floor, which equals 75%; the other 25% is absorbed by the interior surfaces, and the reflected direct radiation from the surfaces is absorbed by all inner surfaces according to their absorptivity; meanwhile, diffuse solar radiation is all absorbed by the inner surfaces;
- The heating demand consumes natural gas with an overall system efficiency of 82%, and the cooling demand consumes electricity with the coefficient of performance (COP), which was 5.6.

6.3.3 Software verification

In order to verify the accuracy of the numerical simulation, this section verifies the feasibility of the simulation software. To be specific, the physical measurements in air conditioned buildings from 0:00 to 23:59 on design day were selected to compare with the simulation results. One thing should be pointed out that, the boundary conditions in the simulation process are consistent with the actual situation (see Fig.6-2). Table 6-3 shows the comparison between the measured and simulated values of indoor temperature at different points in the room under the air conditioned mode.



(a) (b)



(c) (d)

Fig. 6-2. Cloud map of indoor temperature distribution at different heights: (a) X＝0.6m; (b) X＝1.7m; (c) X＝3.3m; (d) Y＝1m.

Table 6-3. Comparison of indoor temperature between simulated and measured value.

	Temperature (℃)		
	Measured value (℃)	Simulated value (℃)	Error (%)
0.6m	22.9	22.4	2.1
1.7m	23	22.7	1.3
3.3m	23.8	22.8	4.2

By comparing and analyzing the measured and simulated values, it can be seen that the two data basically agree with each other, and the error range is all less than 10%, which proves the feasibility of the model and the simulation condition settings, and provides a foundation for further simulation study.

6.3.4 Benchmark cases geometrical model

Given that different climate regions in China have various living customs and also architectural design principles, it is unreasonable and inaccurate to use the same model with all simulations. Thus, in this part, five typical office building models adapted to local climate conditions were established for each climate zone. In order to simplify the models, adjacent rooms with the same functions were merged to decrease the thermal zones of the building. Basic information of the geometrical models are listed in Fig.6-3 and Table 6-4.

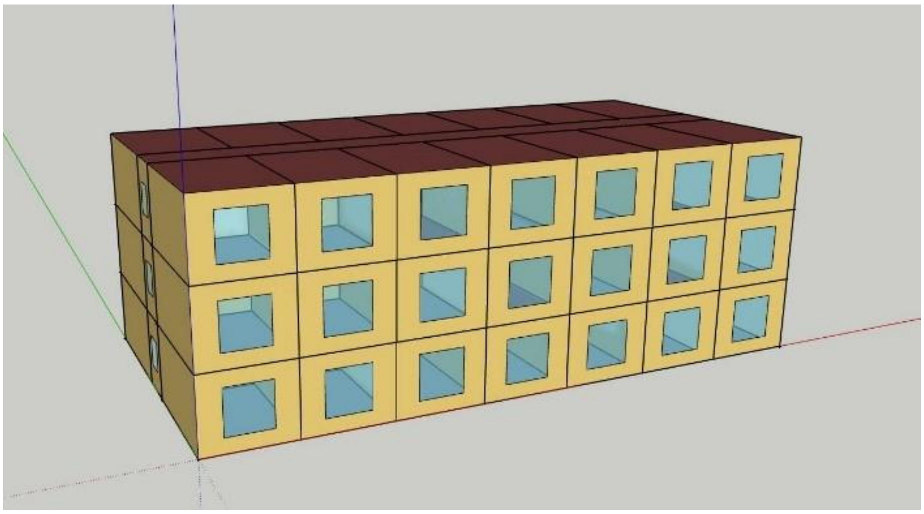


Fig. 6-3. Benchmark cases geometrical model in open studio.

Table 6-4. Geometrical information of benchmark models.

Basic Information	SCZ	CZ	HSCW	HSWW	MZ
	Changchun	Beijing	Shanghai	Haikou	Kunming
Plan area (m^2)	1628.6	1948.8	2012.2	1582.4	1687.2
Number of layers (--)	6	6	6	6	6
Story height (m)	3.5	3.5	3.6	3.6	3.5
Building height (m)	22.2	22.2	22.8	22.8	22.4

6.3.5 Boundary conditions

Since the building envelope is in contact with outdoor environment all the time, heat loss through the opaque/transparent facades should be taken into account seriously, especially in the cold season at night. Therefore, only the insulation design of the envelope can provide a better indoor thermal environment and reduce the energy consumption of the building. Generally speaking, it mainly contains two points: opaque envelope structure (exterior wall and roof) and transparent envelope (exterior window).

Firstly, as the opaque part of the outer envelope, mainly the cold protection and heat insulation should be taken into consideration due to the various climate characteristics. In this part, the brick masonry with low thermal conductivity was selected for the envelope structure in order to increase the adiabatic performance. In addition, thermal insulation materials as a key factor, such as expanded polystyrene (EPS), extruded polystyrene (XPS), rock wool board, and adhesive powder polystyrene insulation, have been widely applied in China nowadays, especially for EPS with its excellent performance and lower price. Thus, this kind of material was also chosen and different thicknesses were set according to the local code so as to find the best result under the premise of satisfying the economic condition.

In addition, in terms of the transparent envelope, it was also important to take adiabatic design for exterior windows into account. Although the larger glass windows can efficiently absorb solar radiation during the day to reduce electrical and heating demand, they are the weakest link in the maintenance structure, which still lose lots of heat at night. Therefore, the double vacuum glazing is a setting that two valuation parameters in this study regarded as having a significant role: U-value of fenestration and SHGC; only a better combination between these two values could minimize the heat loss from the window. One thing worth mentioning is that, since the amount of solar radiation varies across the whole country, SHGC value is not required to be limited in SCZ due to the higher latitude with lower height angle of midday sun, but this should be strictly restricted in other sites on account of the fact that cooling in summer should be focused on reducing the air-conditioning loads. The summary of building envelope conditions for benchmark cases is listed in Table 6-5.

Lastly, other important boundary conditions are given in Table 6-6. According to [26], the indoor design temperature in winter and summer should not be lower than 18 °C or higher than 26 °C. However, due to the individual differences and various self-regulation mechanisms, such a wide range of temperature fluctuations is not considered to be comfortable [27]. Therefore, an optimal interval of 20.5 °C for winter and 25.6 °C for summer was selected in simulation process. Also, traditional architectural thermal disturbance mainly includes people, lighting, and electric equipment loads [28,29], but it has to mention that the air tightness still continuously influences the indoor thermal environment, which is an essential control index to ensure the stability of thermal insulation performance of external fenestration and directly related to the heat loss of cold air infiltration. S. Chen et al. [30] discovered that the heating energy demand would be reduced by 12.6% if the air tightness changed from 1.0 h^{-1} to 0.5 h^{-1}, so the influence of infiltration rate on simulation results was considered in this part.

Table 6-5. Summary of building envelope (opaque/transparent) conditions for benchmark models.

Climate Zones	Exterior Wall		Exterior Fenestration		WWR [--]
	K-Values [W/(m^2 K)]	EPS-Thickness [m]	U-Values [W/(m^2 K)]	SHGC [--]	
SCZ	0.48	0.065	1.46	0.570	0.35
CZ	0.42	0.076	1.98	0.428	0.4
HSCW	0.74	0.036	2.35	0.328	0.4
HSWW	1.38	0.012	2.28	0.30	0.5
MZ	1.24	0.015	2.40	0.332	0.6

Table 6-6. Summary of other boundary conditions for benchmark models.

Climate Zones	Thermal Interference				Design Temperature		Relative Humidity [%]
	People [W/m²]	Lighting [W/m²]	Electric Equipment [W/m²]	Air Changes [h⁻¹]	Winter [°C]	Summer [°C]	
SCZ	11.3	9.0	8.2	0.45	16 (20.5)	28 (25.6)	40-60
CZ	11.3	9.0	8.2	0.5	16 (20.5)	28 (25.6)	40-60
HSCW	11.3	9.0	8.2	0.5	16 (20.5)	28 (25.6)	40-60
HSWW	11.3	9.0	8.2	1	16 (20.5)	28 (25.6)	40-60
MZ	11.3	9.0	8.2	1	16 (20.5)	28 (25.6)	40-60

6.3.6 Optimization scheme

Just as the previous section discussed, the dependent variables of the parametric analysis were heating, cooling, and total consumption of the whole building, as well as the adaptive thermal comfort index. Meanwhile, the following parameters as control variables were optimized with the simulation: ① orientation, ② layer of insulation board, ③ U-value of exterior fenestration, ④ SHGC, ⑤ WWR and ⑥ infiltration rate. The value codomain of these parameters are concluded in Table 6-7.

Table 6-7. Value codomain of the chosen parameters.

Design Parameters	Climate Zones					Number
	SCZ	CZ	HSCW	HSWW	MZ	
Orientation [--]	south, southeast, southwest, west, east					25
Layer of EPS board [m]	0.02, 0.04, 0.06, 0.08, 0.10, 0.12			0.01, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12		32
U-value of fenestration [W/(m²·K)]	1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8		1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4	2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0		47
SHGC [--]	--	0.3, 0.4, 0.5, 0.6, 0.7				20
WWR [--]	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 south and north separately					70
Infiltration rate [h⁻¹]	0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8					50

Note: section 6.4.1 (1-6) adopted the method of single-objective control variable to seek the sensitivity degree of each parameter; section 6.4.1 (7) used the multi-objective method to calculate the sensitivity parameter groups.

6.3.7 Overall workflow

As afore-mentioned, due to the several essential design parameters that should be taken into account seriously at the preliminary design stage, this part adopted the combination of qualitative and quantitative analyses with numerous numerical simulations carried out, so as to search for the best design strategies under the energy consumption and thermal comfort requirement. The specific workflow is shown in Fig.6-4.

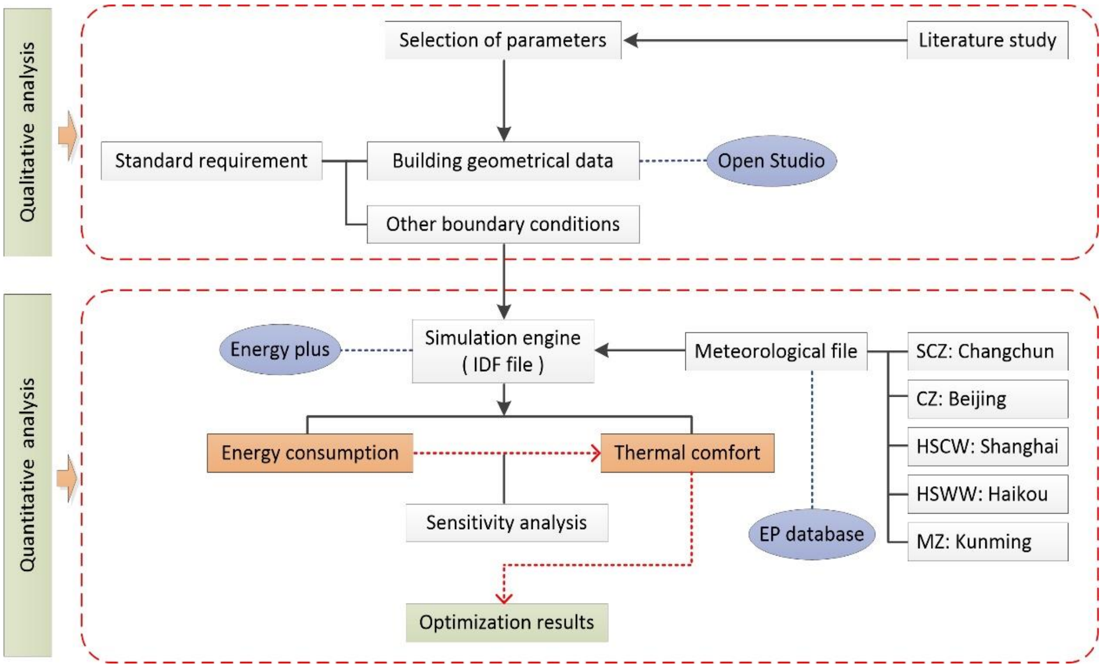


Fig. 6-4. Workflow of optimization process.

6.4 Results and discussion

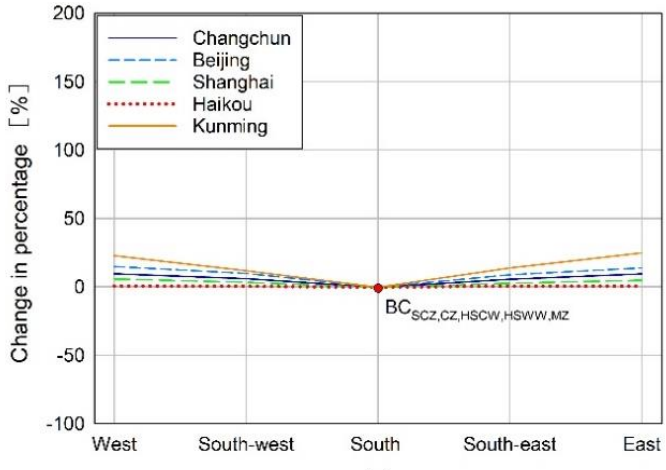
Since there is always an uncontrollable error between weather conditions in a database (average values of a standard year) and local actual meteorological information (random value), the absolute values are not an accurate description of energy utilization. However, a relative variation tendency may be more reliable to reflect the impact of parameter changes on energy demand. Therefore, the influence of each parameter will be presented as percentage change of energy consumption resulting from deviation from base case values. Its calculation could be expressed as Eq.6-3. Where S_i is the percent change, L_i is the energy consumption with changed input parameter and L_n is the energy consumption of benchmark case.

$$S_i = [(L_i - L_n) / L_n] \times 100\% \qquad (6\text{-}3)$$

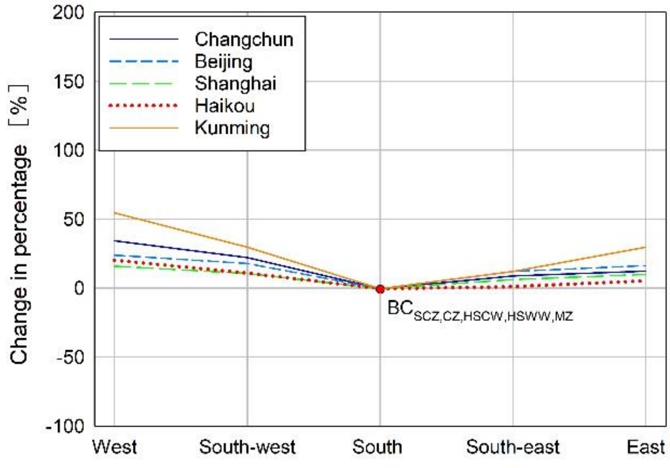
6.4.1 Energy consumption

1) Orientation

According to Fig.6-5 (a-c), it can be easily to find that the optimal solutions of each climate zone are all to the south, given the option of changing the orientation of the whole building. A rotation from south to west or south to east would separately lead to a heating and cooling demand increase of approximately by 5%–25% and 40%–53%, and a maximum growth of about 47% of total energy could be discovered in Kunming. Among them, the influence of orientation on cooling demand was slightly greater than heating.



(a)



(b)

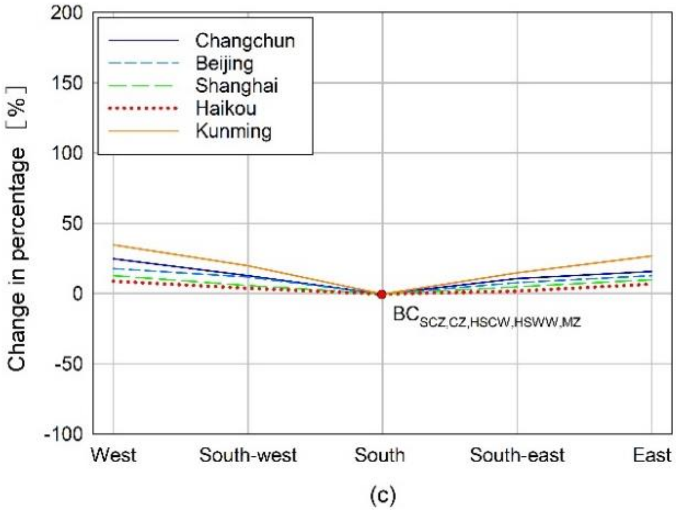


Fig. 6-5. Variation percentage of energy demand for changing orientation [--]: (a) heating; (b) cooling; (c) total.

2) Layer of EPS board

It can be found in Fig.6-6 (a-c) that the changing rates of the terminal energy utilization varied from each other. For heating aspects, adding the thickness of the insulation layer can lead to a significant reduction for energy use in all regions, while the variation in Kunming was minimal, accounting for around 7%. On the contrary, the changing rate of cooling loads lifted, but the amplitude was not obvious. For total energy demand, the results of Changchun and Shanghai revealed the largest energy saving potential of approximately 11% when adding EPS thickness from local standard 0.065m, 0.036m to 0.12m, and then about 6% reduction in Beijing. Nevertheless, by transforming the EPS board from the current requirement values to 0.12 m, the total energy load also increased by around 5% and 20% for Haikou and Kunming, respectively. What needs to be pointed out is that when the variation of total energy consumption for each region is not linearly distributed with the thickness of the material, the rate of change finally flattens out. Therefore, the key point is to search the optimal range of EPS thickness in each city so as to obtain a reasonable balance of energy demand and investment costs.

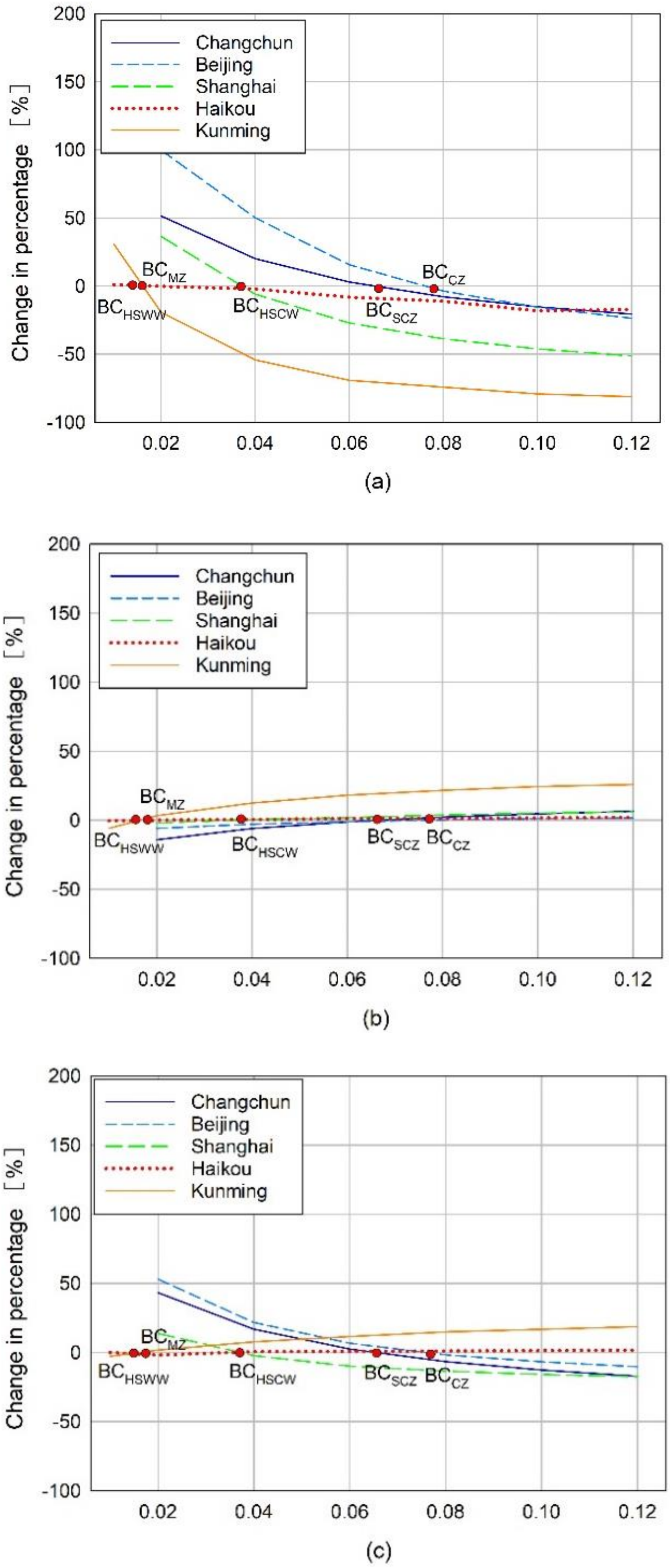
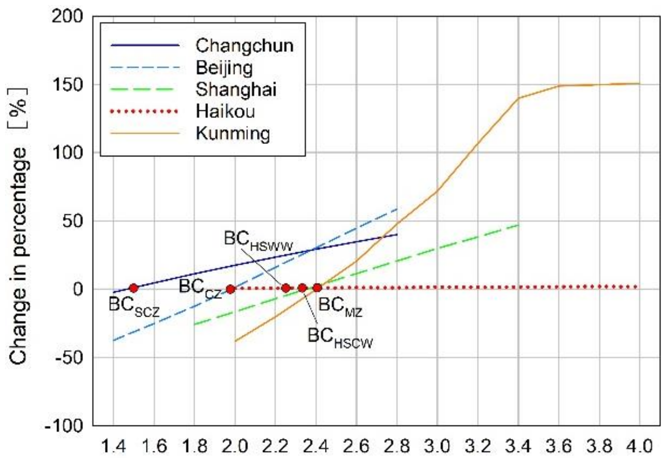


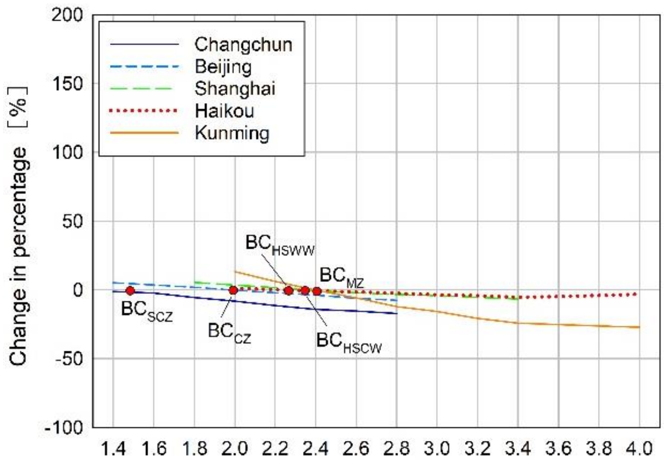
Fig. 6-6. Variation percentage of energy demand for changing layer of expanded polystyrene (EPS) [m]: (a) heating; (b) cooling; (c) total.

3) U-value of exterior fenestration

From Fig.6-7 (a-c), the slopes of the heating and cooling utilizations have different degrees in all cities except in Haikou. For heating aspects, Changchun, Beijing, and Shanghai all grew linearly with U-value increasing, however, Kunming showed a nonlinear growth with an inflection point U-value of 3.4 W/(m^2 K). On the other hand, Beijing and Kunming reflect the best energy saving potential, with approximately by 40% and 37%, respectively. For cooling aspects, the increase variations were all within 10%. Focusing on total demand, only Haikou and Kunming showed a slightly negative growth within 10% by changing the thermal conductivity from standard value to 2.0 W/(m^2 K), which further indicated that the need for heating in these areas is not high in winter and the total energy demand across the year is mainly reflected in cooling; in other words, although the heating reduction was larger than cooling growth in Kunming, the overall utilization was still slightly higher.



(a)



(b)

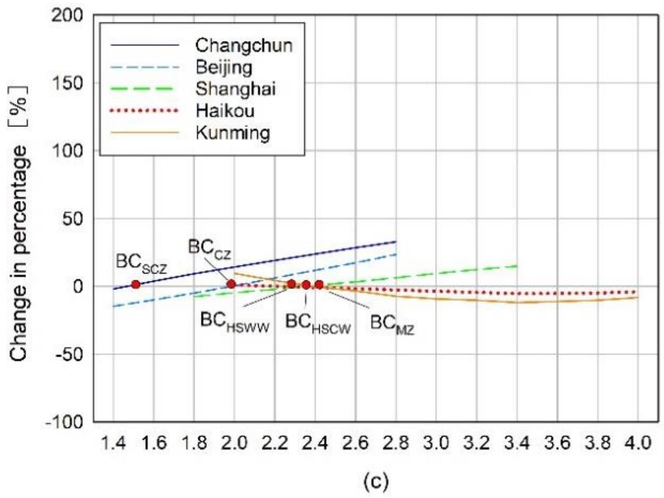


Fig. 6-7. Variation percentage of energy demand for changing U-value of exterior fenestration [W/m^2 K]: (a) heating; (b) cooling; (c) total.

4) Solar heat gain coefficient (SHGC)

Given there is no specific requirement for SHGC value in SCZ, the different values for Beijing, Shanghai, Haikou, and Kunming were carried out respectively, see Fig.6-8 (a-c), and the standard SHGC values for each city above were 0.428, 0.328, 0.30, and 0.332, which are listed in Table 6-5. For heating aspects, all cities except Haikou appeared to have nonlinear reduction for energy utilization by changing SHGC to 0.7, which Kunming has the greatest potential for reaching by 88%, Beijing and Shanghai are both around 72%. However, there is no effect on Haikou due to the fact that the heating demand in winter for this area is the lowest compared to other locations. For cooling demand, the changing of SHGC will affect all cities to varying different degrees, even above the 170% observed in Kunming. For total demand, it was easy to find that, for Beijing, we could appropriately add SHGC at the current standard to save more energy, but it should be strictly limited in Kunming and Haikou. In other words, SHGC is not sensitive to the cold winter regions, but to the warm/hot summer areas of China.

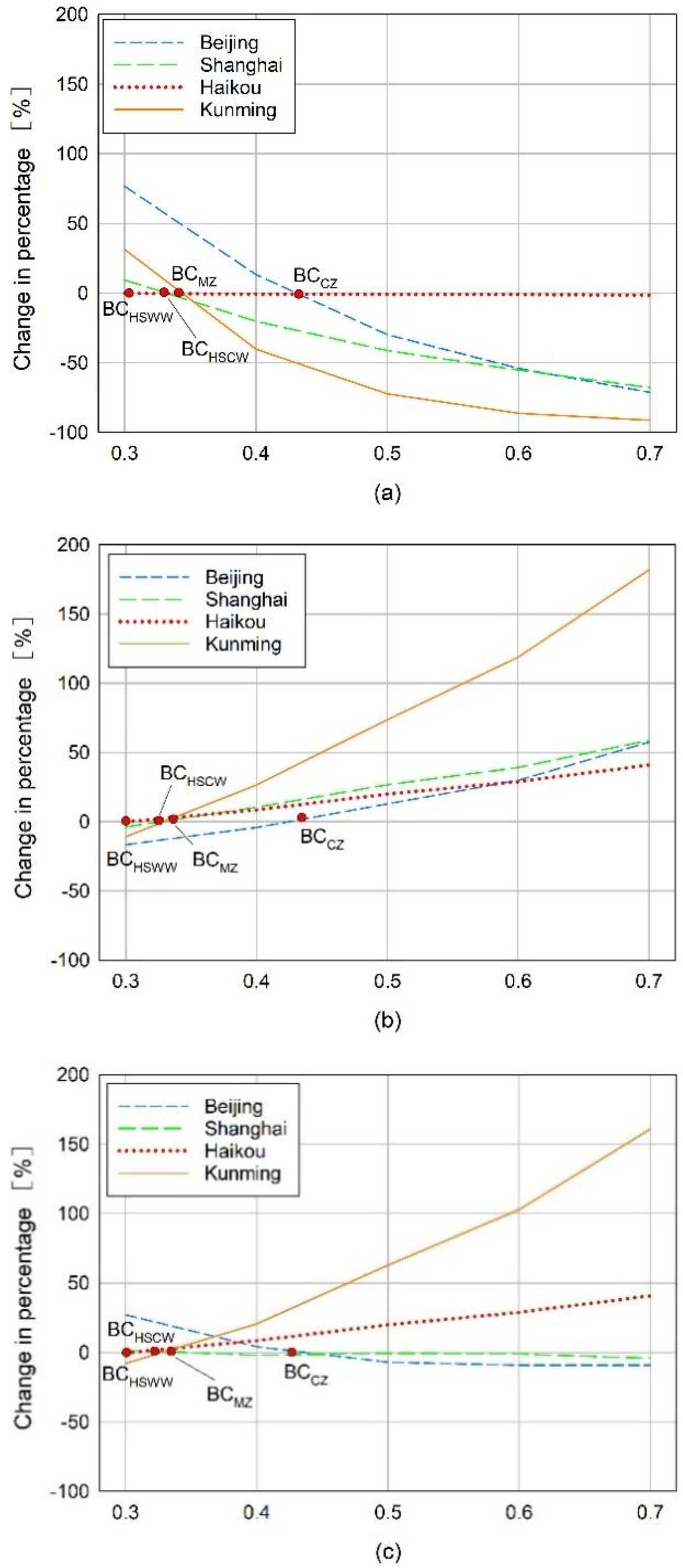


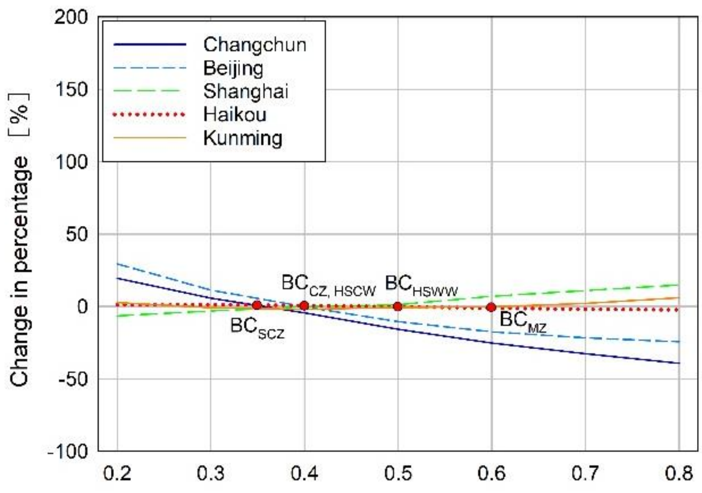
Fig. 6-8. Variation percentage of energy demand for changing solar heat gain coefficient (SHGC) [--]: (a) heating; (b) cooling; (c) total.

5) Window to wall ratio (WWR)

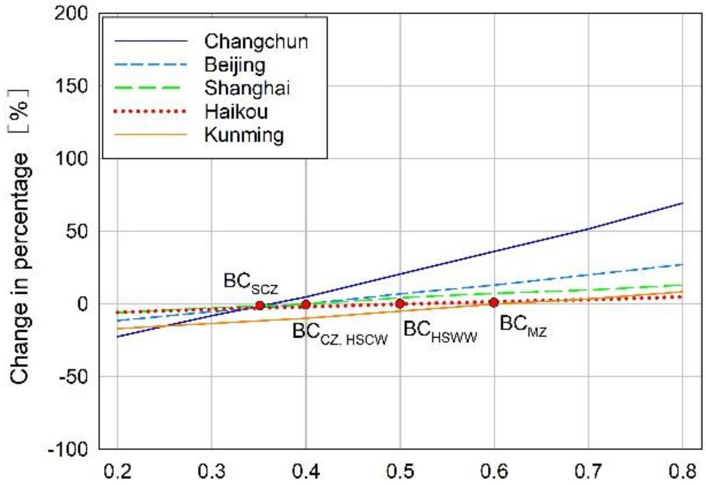
Generally speaking, energy demand varies linearly with WWR in all cities regardless of room orientation. However, due to the fact that the direct solar radiation obtained by south and north facades vary from each other, it is necessary to analyze one by one and then to conduct comprehensive comparison as following.

For south rooms, in Fig.6-9 (a-c), the changing in Changchun was most obvious for total energy savings, which means a larger WWR can effectively receive more radiation. In contrast, the changing in other regions was not obvious; for north rooms, Fig.6-9 (d-f), due to less solar radiation on the facades, the heating loads seemed to have no effect with changing WWR in Changchun, but cooling demand increased by around 40% and the total demand increased in all regions with larger WWR (0.8), especially in Beijing (21%) and Shanghai (20%).

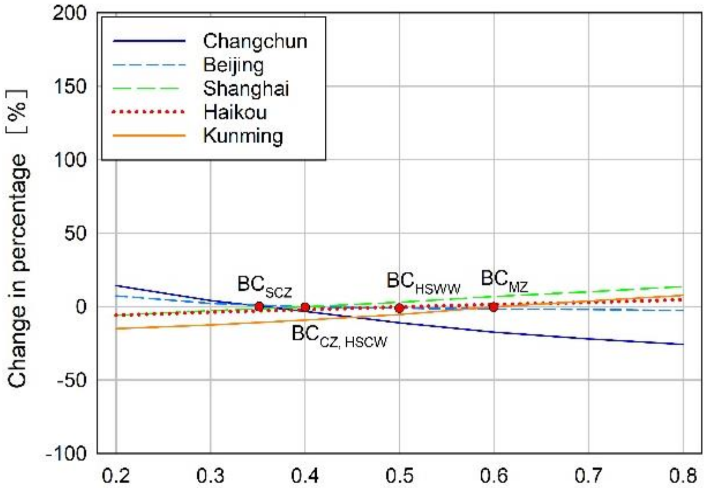
However, by comparing Fig.6-9 (c, f), although the reduction rate in south rooms was larger than the increase rate in north rooms (for Changchun), they seemed to achieve the energy efficiency with larger WWR. One thing worth mentioning is that the initial energy utilization of north rooms was much higher than south, so the rate of change here cannot directly to compare. In other words, for SCZ and CZ of China, indoor heating is easily lost through windows, especially in winter, thus, WWR should also be strictly controlled.



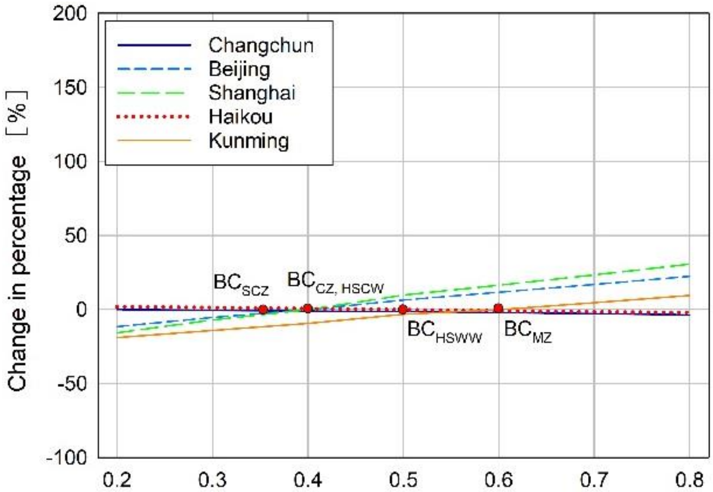
(a)


Changchun
Beijing
Shanghai
Haikou
Kunming
Change in percentage [%]
BC$_{SCZ}$
BC$_{CZ, HSCW}$
BC$_{HSWW}$
BC$_{MZ}$
200
150
100
50
0
-50
-100
0.2
0.3
0.4
0.5
0.6
0.7
0.8

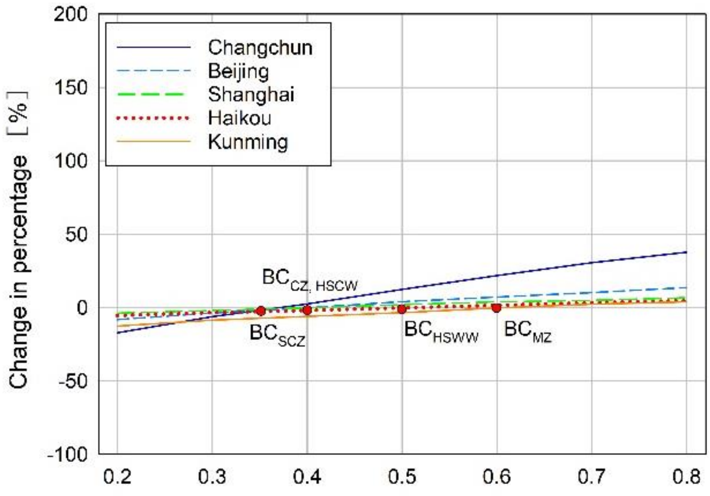
(b)


Changchun
Beijing
Shanghai
Haikou
Kunming
Change in percentage [%]
BC$_{SCZ}$
BC$_{HSWW}$
BC$_{MZ}$
BC$_{CZ, HSCW}$
200
150
100
50
0
-50
-100
0.2
0.3
0.4
0.5
0.6
0.7
0.8

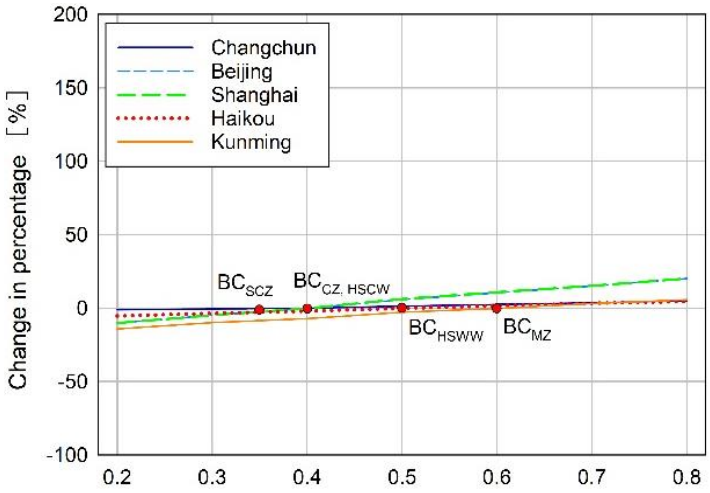
(c)


Changchun
Beijing
Shanghai
Haikou
Kunming
Change in percentage [%]
BC$_{SCZ}$
BC$_{CZ, HSCW}$
BC$_{HSWW}$
BC$_{MZ}$
200
150
100
50
0
-50
-100
0.2
0.3
0.4
0.5
0.6
0.7
0.8

(d)



(e)

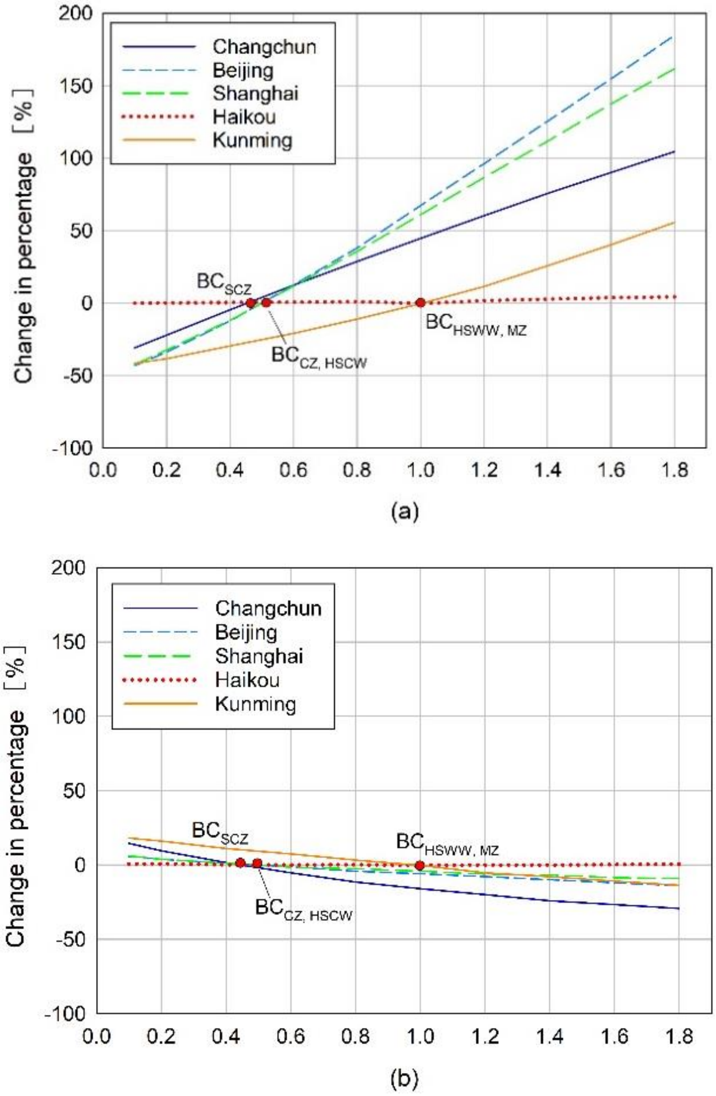


(f)

Fig. 6-9. Variation percentage of energy demand for changing window to wall ratio (WWR) (south/north) [--]: (a) heating--S; (b) cooling--S; (c) total--S; (d) heating--N; (e) cooling--N; (f) total--N.

6) Infiltration rate

According to Fig.6-10 (a-c), for total energy demand, the infiltration rate of Changchun, Beijing, and Shanghai should be taken more into consideration, because the changing rate increased significantly by 85%, 77%, and 60% respectively, which means more heating will be lost in the process of air penetration, and smaller air changes, such as 0.1 h^{-1}, can effectively reduce heat exchanges between indoors and outdoors for energy saving of 18%–26%, and there was nearly no effect on Haikou and Kunming. When focusing on heating and cooling demand separately, infiltration rate and heating consumption increased in direct proportion, which is more significant than that of cooling load in inverse proportion. It is worth mentioning that the energy demand varies linearly in each climate zone regardless of heating, cooling, or total energy demand. However, it is not easy and realistic to reach the 0 h^{-1} due to the fact that cold air infiltration is inevitable and always exists in practical terms. Therefore, the aim should be to decrease the infiltration rate as extremely as possible in cold winter areas. Meanwhile, the appropriate increase in the number of air changes will vary according to the specific circumstances for other regions to reach the objective of energy conservation.



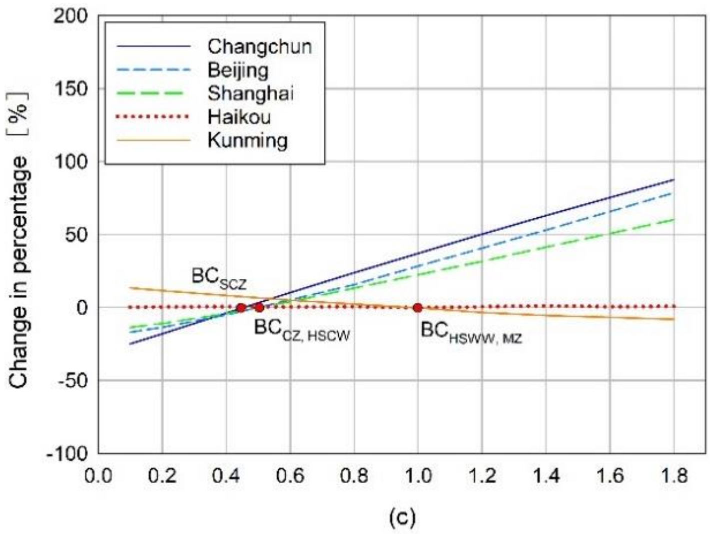


Fig. 6-10. Variation percentage of energy demand for changing infiltration rate [h^{-1}]: (a) heating; (b) cooling; (c) total.

7) Optimal value/range of energy consumption

Through the quantitative analysis above, the sensitivity of each design parameter to different regions was not the same. In this part, by comparing with the current energy codes, further sensitive parameter groups were established to evaluate the energy saving potential, and the final optimal values/range of parameters for each city are shown in Table 6-8.

Table 6-8. Optimal values/range of parameters results of each climate zone.

Design Parameters	Climate Zones				
	SCZ	CZ	HSCW	HSWW	MZ
	Changchun	Beijing	Shanghai	Haikou	Kunming
Orientation [--]	○ South	○ South	○ South	○ South	○ South
Layer of EPS board [m]	● 0.115-0.13	● 0.1-0.13	● 0.08-0.12	○ 0.012	○ 0.02
U-value of fenestration [$W/(m^2 K)$]	○ 1.28	○ 1.28	● 1.78	● 3.0-3.60	● 3.20-3.60
SHGC [--]	○ 0.570	○ 0.5	○ 0.39	● 0.28	● 0.30
WWR [--]	● 0.2-0.32	● 0.2-0.42	○ 0.2-0.4	○ 0.2-0.6	○ 0.2-0.6
Infiltration rate [h^{-1}]	● 0.1	● 0.1	● 0.1	○ 1	○ 1

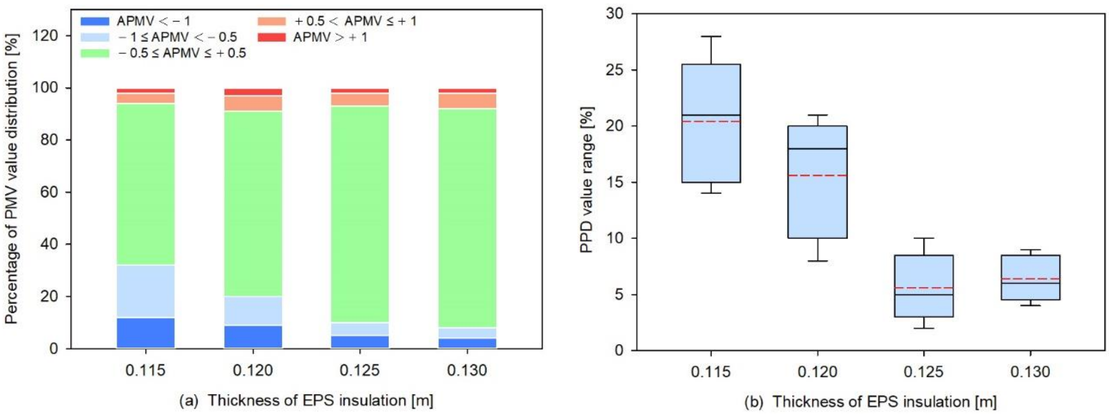
Note: ● represents the most sensitive design parameters; ○ is the subdominant design parameters.

6.4.2 Adaptive thermal comfort

Another significant index which should not be neglected is the increasing desire for indoor thermal comfort, in other words, it needs to meet the maximization of comfort level on the basis of building energy conservation. Thus, in this section, a further calculation was carried out based on the optimal design parameters above to explore the better range for both energy and adaptive comfort requirement. Indoor design temperature in this study was set at 20.5 °C in winter and 25.6 °C in summer. However, the ideal indoor thermal environment cannot be achieved in reality, which means instantaneous temperature will exceed the design range, resulting in thermal discomfort at some certain period of time. This part demonstrates the representative city of different climate zones' APMV/PPD simulation results (8760 h) based on the most sensitive design parameters. What needs illustration is that since the main usage period of office buildings is from 8:00 a.m. to 18:00 p.m. (except for weekends and holiday), the analysis below was also chosen based on this interval.

1) SCZ--Changchun

As is shown in Table 6-8, the most significant parameters of Changchun are EPS thickness, WWR, and infiltration rate. Among them, based on minimum air change (0.1 h^{-1}) being unchanged, the results for various layers of EPS and WWR were achieved in Fig.6-11 (a-d). The results show that an increase of EPS thickness from 0.115 m to 0.130 m improved the indoor thermal comfort range ($-0.5 \leqslant APMV \leqslant 0.5$) by 9%–22%, and as the layer of EPS insulation reached about 0.125 m to 0.130 m, the thermal comfort interval tended to be stable and accounted for more than 80% of the total usage period of the year. Meanwhile, the average values of PPD (red short dotted line) were all below 10%, which can meet level 1 of indoor thermal requirements. On the other hand, an increase of WWR shrank the comfortable range especially from 0.28 to 0.32, which is further indication that the optimal WWR range for this area is approximately from 0.2 to 0.28, which also can be verified from PPD values.



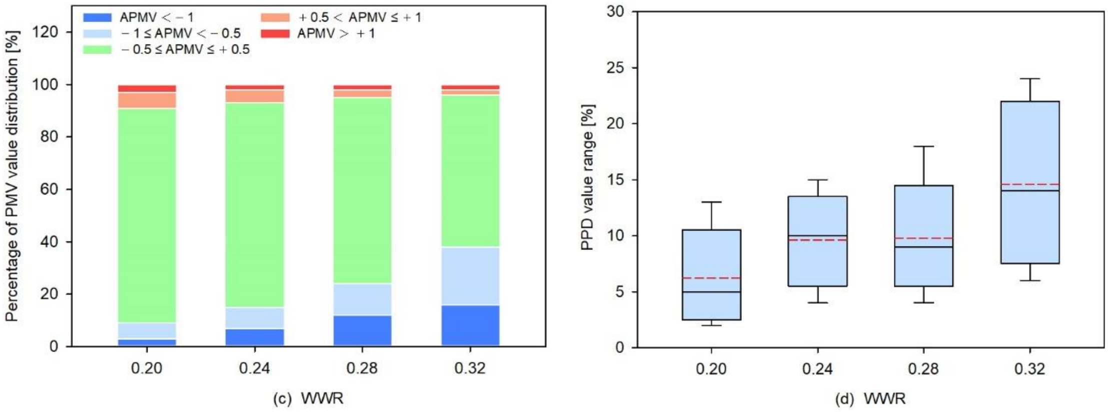
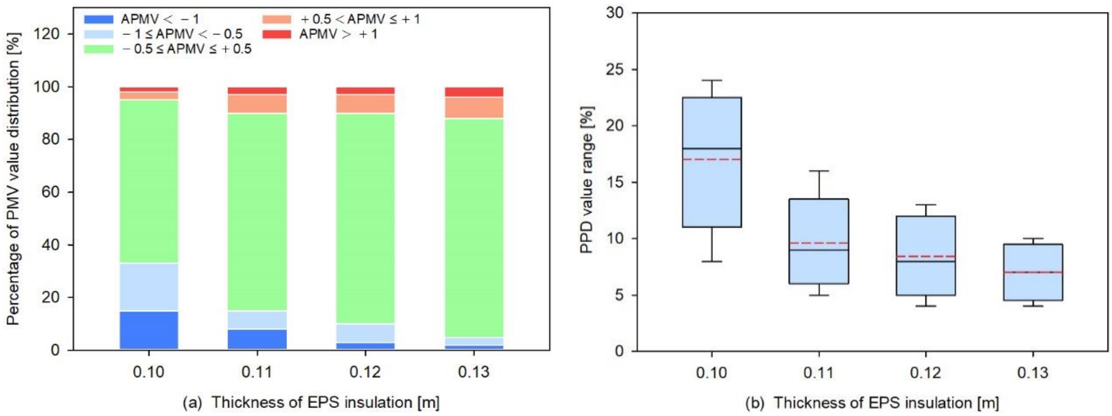


Fig. 6-11. APMV/PPD values of various EPS thicknesses [m] and WWR [--] for a severe cold zone (SCZ)--Changchun: (a) APMV values for changing EPS thickness; (b) PPD values for changing EPS thickness; (c) APMV values for changing WWR; (d) PPD values for changing WWR.

2) CZ--Beijing

Due to the fact that weather conditions between CZ and SCZ are generally similar, the most sensitive parameters for Beijing are still EPS thickness and WWR. According to Fig.6-12 (a-d), an increase of EPS thickness from 0.10 m to 0.11 m will improve the comfort range by about 10%. As the insulation board increased from 0.11 m to 0.13 m, the thermal comfort interval tended to be stable, which accounted for above 83% of the total usage time. At the same time, the mean values of PPD were all below 10%, which can meet the level 1 indoor thermal requirements (9.4%, 8.9%, and 7.6%, respectively). The statistical data illustrated that, no matter how the WWR changed within the chosen scope, the proportions of optimal comfort range all exceeded 85%. To some extent, the optimization results of comfort level in this region for WWR are consistent with the outcome of energy demand.



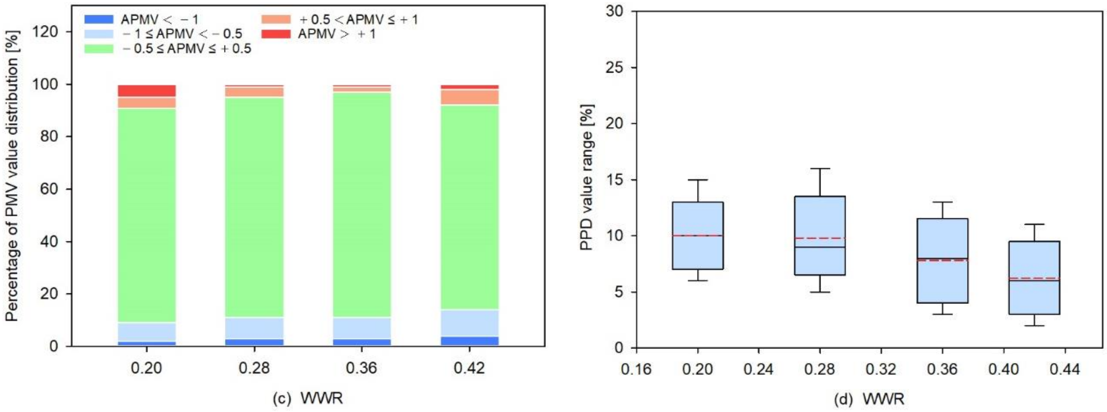


Fig. 6-12. APMV/PPD values of various EPS thickness [m] and WWR [--] for a cold zone (CZ)--Beijing: (a) APMV values for changing EPS thickness; (b) PPD values for changing EPS thickness; (c) APMV values for changing WWR; (d) PPD values for changing WWR.

3) HSCW—Shanghai

Based on the optimal values for energy demand above (Table 6-8), in this region, only the influence for changing layers of EPS on comfort level were focused on. As Fig.6-13 (a-b) shows, by increasing the layer of EPS board from 0.08 m to 0.12 m, the comfort interval (−0.5≤APMV≤0.5) increased first (from 0.08 m to 0.09 m) and then decreased (from 0.11 m to 0.12 m), and the total period of thermal neutrality between the layer was more than 85%, varying from 0.09 m to 0.11 m. Also, the fluctuation range of PPD was relatively small (less than 10%) in this interval.

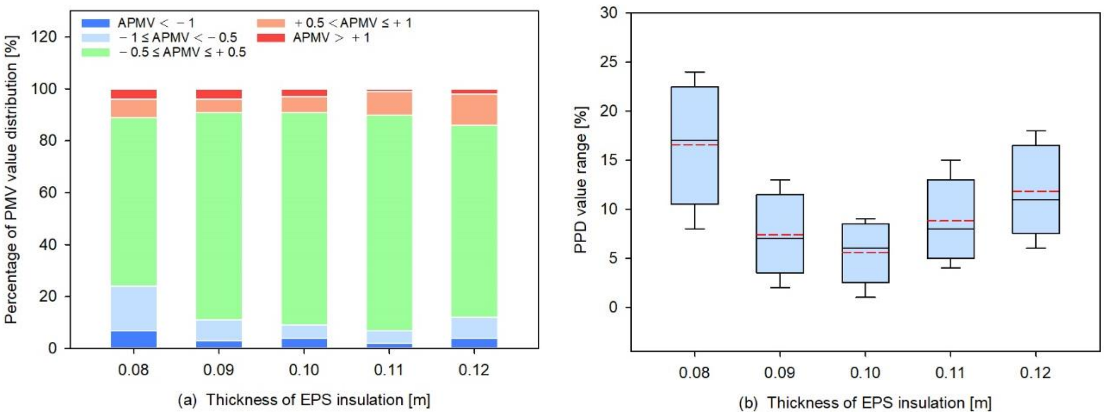


Fig. 6-13. APMV/PPD values of various EPS-thickness [m] for a hot summer and cold winter (HSCW)--Shanghai: (a) APMV values for changing EPS thickness; (b) PPD values for changing EPS thickness.

4) HSWW—Haikou

In this area, since cooling loads contribute the main portion of total energy demand, the U-value of exterior fenestration and SHGC become more important. From Fig.6-14 (a-b), based on optimal values of SHGC (0.28), only the impact for transforming U-value of exterior fenestration on comfort level was concentrated on. With changing the U-value from 3.4 to 3.6 W/(m^2 K), the partition of light red increased significantly, which means the higher conductivity of fenestration led to a rapid rise for indoor temperature, and the total periods of thermal neutrality between the U-values were more than 78%, varying from 3.0 to 3.2 W/(m^2 K), and the fluctuation ranges of PPD were both less than 10% in this range.

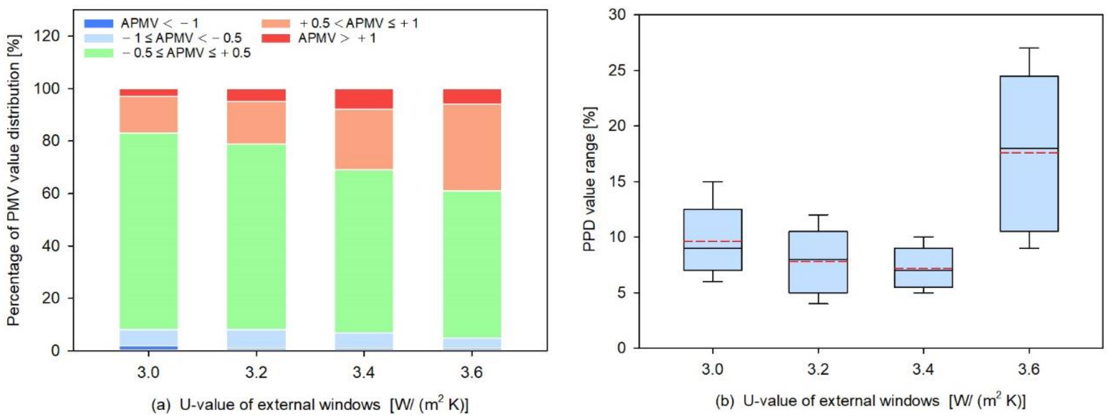


Fig. 6-14. APMV/PPD values of various U-value of exterior fenestration [W/m^2 K] for a hot summer and warm winter zone HSWW--Haikou: (a) APMV values for changing U-values; (b) PPD values for changing U-values.

5) MZ—Kunming

Just as in the situation of HSWW, only the impact of altering U-value on comfort level was focused on. As Fig.6-15 (a-b) shows, by changing the U-value from 3.2 to 3.6 W/(m^2 K), the comfort interval of level 1 increased first (from 3.2 to 3.4) and then decreased (from 3.4 to 3.6), and the total periods of thermal neutrality between the range of 3.3 to 3.5 W/(m^2 K) were more than 78%. Also, the average values of PPD were all within 10%, respectively.

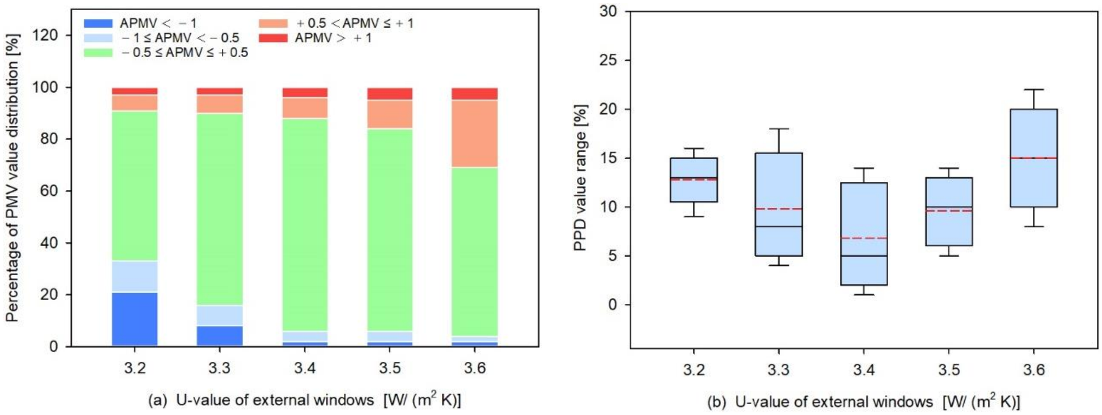


Fig. 6-15. APMV/PPD values of various U-value of exterior fenestration [W/m^2 K] for mild zone (MZ)--Kunming: (a) APMV values for changing U-values; (b) PPD values for changing U-values.

6.4.3 A trade-off consideration between energy consumption and adaptive comfort

The calculation results above indicated the combination of sensitive parameters that minimized energy demand while maximizing the thermal comfort condition for urban office buildings in five representative climatic regions of China. Annual end-use and total energy demand of parameter variations were compared with benchmark cases to evaluate the energy saving potential.

For SCZ, considering that the heating requirement dominates the larger part of energy utilization, although the solar energy can reduce the heat loads to some extent during the day, the heat loss at night is still much larger than that of the sun. Therefore, the primary consideration is to increase the heat storage performance of the building envelope. In other words, setting the larger thermal inertia of the surface material and appropriately increasing the thickness of the insulation layer can effectively improve the thermal delay of the building envelope, which can take the radiant heat of the day and contribute this to the night so as to reduce the initial heat loads of the next usage period. Similar strategies can also be applied to CZ, because the climate distribution is roughly the same as SCZ. One point which cannot be neglected is that the fenestration size with lower infiltration rate is also significant in these areas. The reason for this is that transparent glass is the most vulnerable part of the envelope and cold air permeation always exists, so only taking the envelope material, WWR, and infiltration rate into account seriously can achieve the unification of energy efficiency and thermal comfort. In terms of HSCW, avoiding overheating in summer and heating protection in winter should being weighed up. By optimizing the U-values of the exterior transparent/opaque envelope as well as the infiltration rate, approximately one fifth of the total energy consumption can be saved. Meanwhile, a higher level of comfort requirement can be achieved through transforming the layer of insulation materials. Since the overheating is dominant in HSWW, the practical approach is to coordinate the relationship between U-values of exterior window and SHGC, a larger value of SHGC will lead to the cooling loads increasing at an alarming rate, also resulting in discomfort indoors. When focusing on

MZ, although temperature variations are minimum in the whole year, the SHGC and U-values of windows are also sensitive in this area, the former of which can provide free heat in winter but can also lead to overheating in summer, thus, the additional constraining factors (heat transfer coefficient of fenestration) seem more important for obtaining the higher comfort interval.

6.5 Summary

In this chapter, the optimization results of various parameters for each climate zone were presented with consideration of energy demands as well as adaptive thermal comfort. Firstly, the design parameters which were considered to be likely to affect energy utilization were extracted from the literature review, and five typical benchmark cases with climatic adaptability were established for further quantitative analysis. In addition, with the help of numerical simulation, it was found that the influence of parameters on different climatic zones are not the same. Meanwhile, the parameter groups were set up according to the sensitivity level of each climate region to explore the maximum energy reduction. Lastly, a further coupling calculation of indoor adaptive thermal comfort based on the optimal energy consumption interval was conducted to search for the best thermal range with less energy consumption. The main conclusions are summarized as follows:

- In general, buildings oriented south have the best performance for energy consumption across all five climate zones, because they can make full use of the solar radiation and achieve the basic day-lighting requirement.
- SCZ—Changchun: due to the fact that heat protection in winter is the most significant aspect, the insulation thickness, WWR, and infiltration are more sensitive when the thickness of EPS insulation varies from 0.125 m to 0.130 m and WWR is less than 0.24, and when the other parameters remain unchanged at the optimal values (infiltration rate is as small as possible), buildings in this climate can reach the maximum total energy demand reductions of about 18%–24%. Meanwhile, with the improvement of the building envelope, a comfortable condition will be maintained at the higher level.
- CZ—Beijing: similar to SCZ, the thermal insulation performance of the envelope structure is still an important issue in this area, and the biggest energy saving rate can reach approximately 15% when the EPS thickness is between 0.11 m to 0.13 m, with the best WWR range being from 0.2 to 0.42.
- HSCW—Shanghai: since both energy demands (heating/cooling) should be taken into consideration in this area, the results showed that when the most important parameters of EPS insulation change from 0.09 m to 0.11 m, this can achieve the biggest energy reduction of 16%–19%, and although it can reduce heating loads while continuing to increase the insulation layer, indoor discomfort (slight warm) will exist in summer.

- HSWW—Haikou: as overheating is the main issue in this region, it is essential to take measures for avoiding high temperatures in summer to reduce the cooling loads. For one thing, maintaining the optimal value of SHGC and other subdominant parameters based on the simulation results invariably, and for another, setting the U-value of fenestration between 3.0 W/(m^2 K) and 3.4 W/(m^2 K), can receive the best saving of 5%–7%, as well as guarantee a higher comfort level.
- MZ—Kunming: comparing with HSWW, the crucial influence parameters are also SHGC and U-value of exterior fenestration, so it was found that a U-value between 3.3 W/(m^2 K) and 3.5 W/(m^2 K) while also keeping SHGC as small as possible based on local standards will lead to approximately 12%–15% of total energy demand reduction.

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Chapter 7

CONCLUSION AND PROSPECT

Content

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7.1 Conclusion

Human thermal comfort as an eternal theme, which was explored in public buildings in China by considering the energy consumption. Generally speaking, the study for thermal comfort mainly including static theory and dynamic theory. In current thesis, dynamic approach was adopted to conduct the researching process which mainly supported by the two models, namely adaptive comfort model and adjustment PMV model. As for the former, the adaptive model was built via investigation study and data regression analysis. It should be make full use of the occupants' thermal adaptability under the specific environment, so as to provide reference values for the revision of local energy-saving standard. For the latter, the adjustment PMV model was established in Energy Plus through the simulation method. Above all, the conclusions of this research can be summarized as following.

In chapter one, **INTRODUCTION AND PURPOSE OF THE RESEARCH**. Firstly introduced the background of the research topic. Under the premise of saving building energy consumption, it is of great practical significance to meet the thermal comfort of human body to the greatest extent. In addition, the development status of the thermal comfort were reviewed. And then proposed the target of the research based on the questions raised.

In chapter two, **LITERATURE REVIEW**. The two main research ideals of the adaptive approach were presented. From which the adjustment PMV model was used PMV value that predicted by steady-state heat balance theory to establish the actual thermal sensation of human beings in non-air conditioned buildings, and the specific revised methods were expressed as expectancy factor “e”, adaptive coefficient “λ” and the△PMV (deviation between PMV and TSV). The adaptive comfort model was based on statistical method, and the comfort temperature or acceptable temperature range varied with outdoor climate. Furthermore, focused on the adaptive model, three aspects namely field investigation, climatic adaptability and application were reviewed, respectively.

In chapter three, **RESEARCH METHODOLOGY**. Introduced the two approaches of climate classifications, namely Köppen-Geiger climate classification and Chinese climate regionalization. In addition, the establishment methods of the two models mentioned above were explained in detail (investigation study for adaptive model and simulation study for adjustment PMV model). Lastly, combined with the evaluation indexes extracted, the whole research process was described in detail.

In chapter four, **INVESTIGATION STUDY ON ADAPTIVE THERMAL COMFORT IN EVAPORATIVE COOLING AIR CONDITIONED BUILDINGS**. Based on adaptive comfort model, a systematic investigation for public building standard rooms with evaporative cooling air conditioned system (ECS) in Urumqi (China) was conducted. Meanwhile, the authentic indoor physical environment and actual thermal comfort were surveyed. Through the regression analysis, the neutral (comfort) temperature, preference temperature and acceptable temperature range in ECS buildings were determined, respectively. Ultimately, the adaptive model was established by using the relationship between outdoor prevailing mean temperature and indoor comfort temperature.

In chapter five, **INVESTIGATION STUDY ON ADAPTIVE THERMAL COMFORT IN EVAPORATIVE COOLING AIR CONDITIONED AND NATURALLY VENTILATED BUILDINGS**. Based on adaptive comfort model, a pilot study was unfolded for different operation modes between evaporative cooling air conditioned and naturally ventilated buildings in Turpan (China). At the same time, surveyed the authentic indoor physical environment and actual thermal comfort for each mode, and obtained the neutral temperature and acceptable temperature/relative humidity/air velocity range. Furthermore, the differences of selective behavior adjustment were concluded, and verified the accuracy of recommended models in ASHRAE-55, EN 15251 and Chinese GB/T 50785 comparing to each mode.

In chapter six, **SIMULATION STUDY OF DIFFERENT REGIONS ON ADAPTIVE THERMAL COMFORT**. Based on adjustment PMV model, the optimization results of various parameters for each climate zone were presented with consideration of energy demands and adaptive thermal comfort by simulation. Firstly, the design parameters which were considered to be likely to affect energy utilization were extracted from the literature review, and five typical benchmark cases with climatic adaptability were established for further quantitative analysis. In addition, with the help of numerical calculation, it was found that the influence of parameters on different climatic zones are not the same. Meanwhile, the parameter groups were set up according to the sensitivity level of each climate region to explore the maximum energy reduction. Lastly, a further coupling calculation of indoor adaptive thermal comfort based on the optimal energy consumption interval was conducted to search for the best thermal range with less energy consumption.

In chapter seven, **CONCLUSION AND PROSPECT**. The conclusions of the whole thesis was summarized and the future work of the adaptive thermal comfort have been discussed.

7.2 Prospect

In this thesis, the thermal comfort of buildings in climate representative areas of China was studied from the point of view of thermal adaptability. However, as we all know, the three adjustment ways (behavioral, physiological and psychological adjustment) were not exist in isolation or acted independently, people's subjective response and evaluation to the environment were the coupling results of the three. In other words, how to truly quantify the coupling relationship between the three is the next issue to be considered. It can be summarized as follows.

- How to quantify the weight of expectation factor of psychological scale regarding the past and future for human comfort?
- To explore the influence of other disciplines such as environmental psychology on thermal response.
- To probe the subjective physiological response of the same race to environmental changes in different generations.

- To research the long-term potential effects of physiological emergency responses under extreme climatic conditions.
- To study the psychological expectation threshold of similar individuals to environment in different time and space.
- Based on the issues mentioned above, how to unfold the thermal comfort study under the paying willingness of the energy consumption.