Chapter 1
Introduction

1.1 Background

China building sector has been growing rapidly in recent years. From 2000 to 2013, the urban residential area increased from 9.5 to 23.4 billion m^2. Figure 1.1 shows that Chinese total building energy consumption increased from 320 to 756 million tce. Under this context, how to effectively control building energy consumption and improve building environment quality has become a hot topic. According to a strategy named ‘total energy consumption control’, if the total building area in the country will be 80 billion m^2 in future, the corresponding energy consumption in should be controlled at 1.1 billion tce. Which means the maximum building energy intensity is

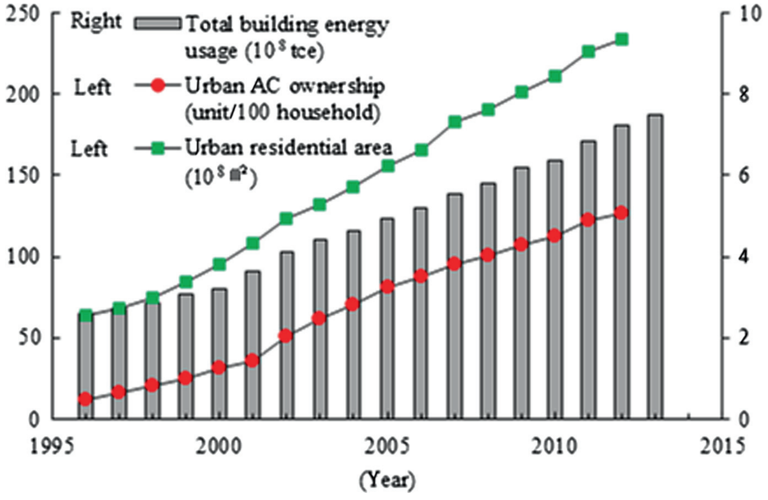


Fig. 1.1 China’s urbanization process from 1996 to 2013 [2]

13.7 kgce/m^2, equivalent to 30% of current building energy intensity in the United States or 40% of that in Japan and Germany [1].

With the development of economy and living standard improvement, Chinese people's pursuit of building environment quality is getting higher, caring more about comfort and health aspects of buildings. It is essential to create sustainable indoor environment without exceeding the upper energy intensity limit. Among all the building energy consumption ends, heating, ventilation, and air conditioning (HVAC) system take up 40% of the total building energy consumption [1]. Proper design and operation of the HVAC system can help to meet occupants' health and comfort requirement meanwhile lower the energy expenditure.

1.1.1 Practical Values of Thermal Comfort Research

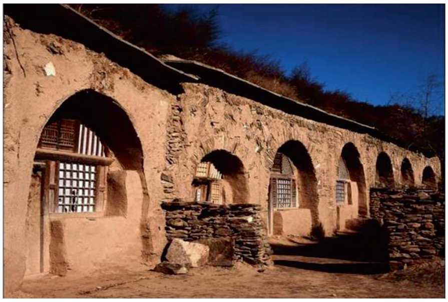
Thermal comfort studies, especially adaptive thermal comfort research, can help to fulfill this aim by providing a basis for indoor thermal environment evaluation. Firstly, the adaptive thermal comfort phenomenon can support the climatic building design strategy other. The traditional architecture forms in different climate zones are a historical confirmation of how buildings should adapt to local climate [3–5]. North China is hot humid in summer but cold and dry in winter. So that its local 'Si He Yuan' buildings (Fig. 1.2a) can keep residents warm in winter but provide shading in summer. The "Cave dwelling" in the loess plateau in northwest China (Fig. 1.2b) is well adapted to climates with large annual temperature variance. In southwest China, residents created the "Gan Lan" building (Fig. 1.2), which successfully protect occupants from rain, moisture, and heat.

In addition, adaptive thermal comfort research can help understand the changing trend of people's requirements on the thermal environment. Taking air conditioning as an example. Figure 1.3 shows the trends of residential AC penetration (or adoption rates) in different countries. Although the growing periods varied, the sharp increasing trends in these economic or demographic superpowers were shocking. A study [6] looked in particular at Mexico, where AC penetration was only about 13% in 2012 and forecasted that as people get richer, those living in warm climates will flock to AC with 2.7% ownership growth per $1000 of annual household income. More worrying, similar things will happen not only in Mexico but also in low and middle-income countries around the world.

1.1.2 Challenges in Adaptive Thermal Comfort

In the long history of mankind, the use of fire extended the range of human activity from tropical areas to colder areas. It has been widely used in buildings as fire basin, fire Kang, firewall, fireplace, etc. Among which the fireplace is still in use in modern

(a) Si HeYuan



(b) Cave dwelling

(c) Anhui architecture

(d) Gan Lan

Fig. 1.2 Typical climate adaptive buildings in China

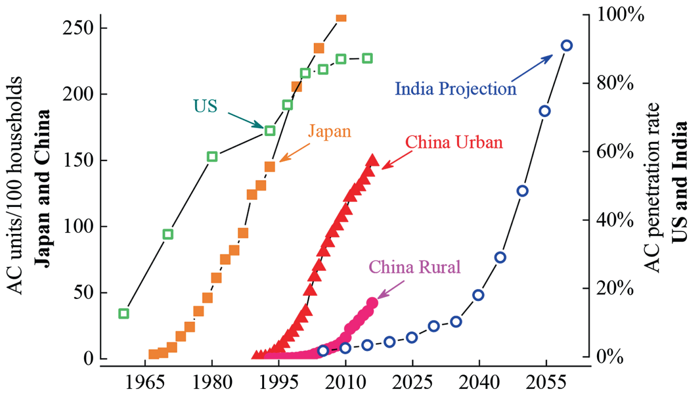


Fig. 1.3 Increasing trend of air conditioner penetration or adoption rate (US data is from Ref. [7], Japanese data is from Ref. [8], Chinese data is from Ref. [2], India data is from Ref. [9])

buildings. Compared to fire, mechanical heating and cooling like HVAC devices have a much shorter history. The first electric air conditioner was invented until 1902 by Dr. Carrier [10]. Early air conditioning aimed to meet manufacturing process demand.

Figure 1.4 shows a brief history of thermal comfort research. In the 1970s, due to the popularization of HVAC products, intensive thermal comfort studies were conducted to answer how do different thermal conditions influence human thermal comfort. Professor Fanger in Denmark Technology University developed the Predicted Mean Vote—Predicted Percentage of Dissatisfaction (PMV-PPD) model [11] based on human body heat balance to correlate subjective comfort status with objective thermal conditions. Since then, the model has been widely adopted by standards such as ISO 7730:2005 [12], American standard ASHRAE Standard 55-2013 [13], European standard CEN 15251 [14] and Chinese national standard GB/T 50785 [15].

Different from the PMV model, adaptive thermal comfort research pays more attention to building occupants' role in maintaining themselves in comfort status [16], and the adaptive models based on field studies are closer to occupants' actual feeling [17–20]. Among the existing adaptive models, the one developed by Professor de Dear [21] is the most widely influenced.

However, the PMV and adaptive comfort model are two separate models and they may be incompatible sometimes. When applying these two models in real buildings, there may occur awkward issues. For example, the current standards simply classify buildings into two categories, i.e., air conditioning (AC) buildings and nature ventilation (NV) buildings, in a black-and-white way. The PMV model is suitable for AC buildings, while the adaptive model is suitable for NV buildings. But in the real world, buildings can be much more complicated. Given that mixed-mode (MM) buildings usually have mechanical air conditioning that coexists with natural passive cooling [22, 23], there is no consensus on the thermal comfort standard that should be applied to mixed-mode buildings. As shown in Fig. 1.5, if different models were applied to evaluate MM buildings, the results can be completely different.

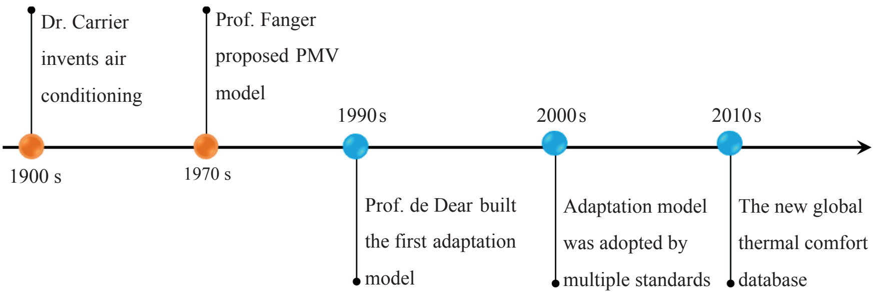


Fig. 1.4 A brief summary of thermal comfort research

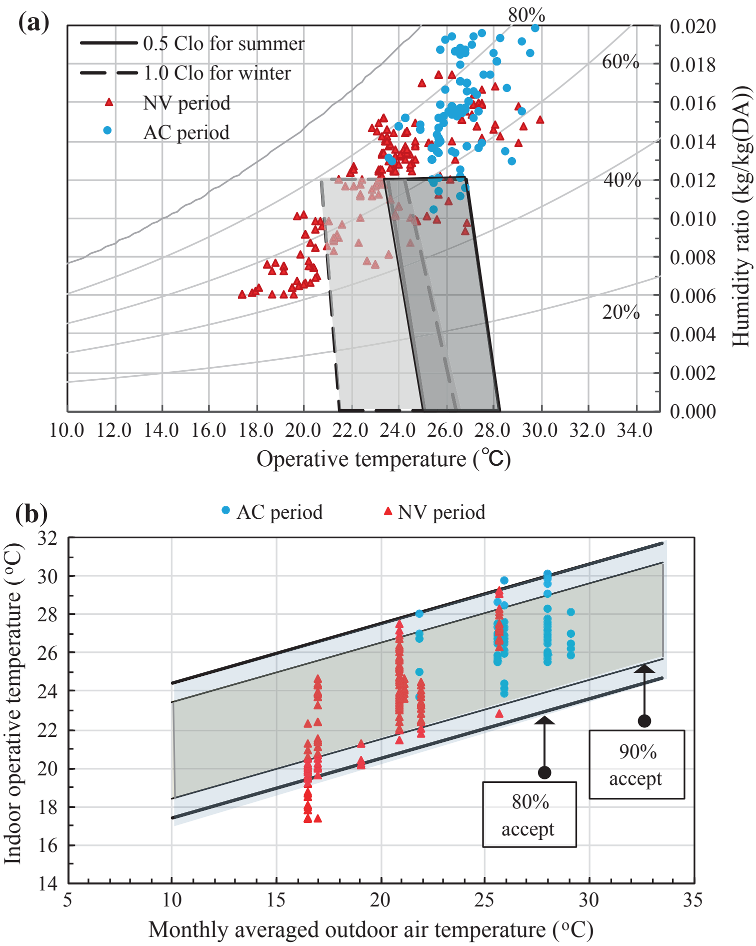


Fig. 1.5 Thermal comfort in MM building: **a** PMV model, **b** adaptive comfort model

1.1.3 New Progress in Adaptive Thermal Comfort Research

Although adaptive thermal comfort research already has a nearly 30-year history, it is still a hot topic in the field. In the past several years, a new thermal comfort database for building environment has been gradually established, including 6 continents, 23 countries, and 81,846 samples (see Fig. 1.6). The new database aims to make up the defects in the first ASHRAE thermal comfort database (RP-884) in terms of data uniformity, sample representativeness and time validity [24]. So that it is promising to establish adaptive thermal comfort model with a wider application range. However, large-scale empirical data can only reflect the phenomenon while

Fig. 1.6 ASHRAE global thermal comfort databases [25]

missing the underlying reasons. If an adaptive comfort model with a wider adaptation range is to be established, more clear mechanism of thermal adaptation and larger data sample should be mutually verified.

At the same time, a project in the International Energy Agency (IEA) on Energy Conservation in Buildings and Communities, ANNEX 69, has been launched. The proposal aims to improve the adaptive thermal comfort theory and apply it to the design and operation of low-energy buildings. Nearly 30 research institutions in 12 countries have actively participated in the project. The international cooperation platform provides favorable conditions for further research on human thermal adaptation mechanism in buildings.

1.2 Literature Review

Generally, thermal comfort research involves many specific areas, such as outdoor thermal comfort and urban planning [26, 27], indoor thermal comfort and productivity [28–30], thermal comfort and building energy consumption [31, 32], thermal comfort under different scenarios [33–37] and so on. Given the objectives of this thesis, the above topics will not be introduced in detail here. Relevant contents can be referred to relevant reviews [38, 39]. This section mainly summarizes steady-state thermal comfort studies and adaptive thermal comfort studies.

1.2.1 Thermal Comfort Introduction

Thermal comfort study in buildings belongs to physiological psychology research. It involves physics, physiology, psychology, and even culture disciplines. Figure 1.7 shows the relationships between building environment and human body heat transfer. The building envelope and clothing together form a microclimate that affects our subjective feelings meanwhile involving different forms of heat and moisture transfer. Human body temperature regulation involves multiple physiological regulation processes. Human perception of the surrounding environment involves psychological processes. All these multi-discipline interactions increase challenges to thermal comfort research. Under such background, the basic method of thermal comfort research is objective quantification of subjective feelings, i.e. using a series of quantification rules to correlate subjective feelings with physical heat balance status.

'Thermal sensation' is a commonly used term in thermal comfort research to describe the subjective feeling of the human body after being stimulated by cold and heat. Since subjective perception cannot be directly measured by instruments, questionnaires like thermal sensation vote (TSV) are used to quantify the 'sensation'. Historically, there have been different TSV scales [41, 42], of which the 7-point scale (shown in Fig. 1.8) recommended by ISO [12] and ASHRAE standard 55 [13] is the most widely used. TSV can effectively correlate subjective thermal sensation and objective thermal condition.

Similarly, to quantitatively describe the subjective 'comfort' perception, thermal comfort vote (TCV) is commonly used. Figure 1.9 shows a quantitative voting scale

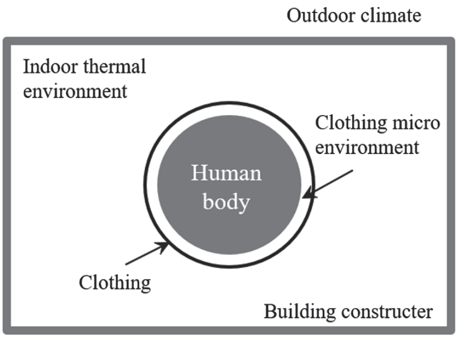


Fig. 1.7 Buildings, occupant, clothing, and the environment [40]

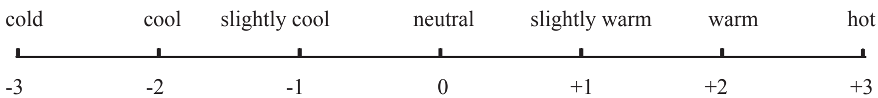


Fig. 1.8 Seven-point scale TSV

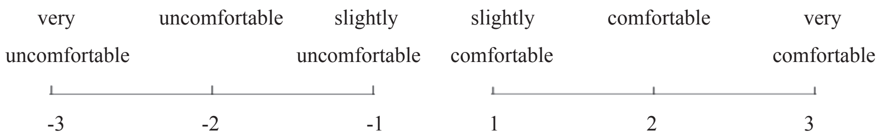


Fig. 1.9 Thermal comfort vote scale

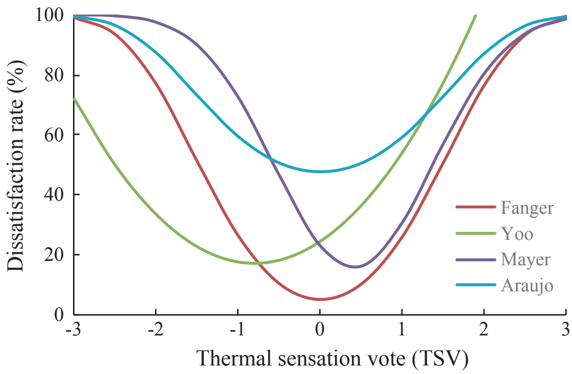


Fig. 1.10 The correlations between TSV and other comfort votes [46–49]

of TCV. In addition, other comfort metrics like Satisfaction Rate Vote, Thermal Preference Vote, Humidity Perception Vote, Air Movement Preference Vote are widely used as well [43].

There is a certain correlation between TSV and other comfort voting. So that TSV is often used as an indicator to reflect comfort and satisfaction status. For example, Fig. 1.10 shows the relationship between TSV and TCV. When thermal sensation is neutral (i.e. TSV $= 0$), it corresponds to the state of "neither cold nor hot". Many researchers believe that the most comfortable state occurs when our body has the least thermal stress. When thermal sensation deviates from neutrality (i.e. TSV $\neq 0$), the heat balance status of our body is broken, thus the thermal comfort perception would decline correspondingly [11, 44]. It is believed that when TSV is maintained within ± 0.5, over 90% of occupants should feel comfortable and satisfied. When TSV is maintained within ± 1, over 80% of occupants should feel comfortable and satisfied. According to this assumption, maintaining TSV between -1 and 1 is widely used in real HVAC control [45].

1.2.2 Heat Balance Comfort Models

1.2.2.1 Comfort Indexes Related to Human Body Heat Balance

Factors that affect human body heat balance include air temperature, radiation, relative humidity, air movement, clothing insulation, activity intensity, etc. [50]. Heat balance-related model describes the influence of different thermal parameters on human body heat dissipation according to heat transfer principles. And then correlate human body heat balance state to subjective thermal sensation. To date, several comfort indexes have been put forward. Table 1.1 summarizes the major features of these indexes.

The predicted mean voting (PMV) considers environmental parameters (air temperature, air velocity, radiant temperature, and relative humidity) and personal factors (activity intensity and clothing insulation) as input variables, and then calculates heat balance status of the human body and associates it with the seven-point TSV. The operative temperature (t_{op}) comprehensively considers the influence of air temperature and radiant temperature on human body heat balance. ET, SET, and WBGT can convert other thermal parameters like solar radiation into the influence of air temperature. UTCI calculates skin temperature through a multi-node heat dissipation model of the human body and then correlates TSV with skin temperature.

Among the indexes listed in Table 1.1, PMV and SET are adopted by the ISO 7730:2005 standard, American ASHRAE Standard 55-2013, European CEN 15,251 standard, and Chinese GB/T 50785 standard, and etc. The PMV is widely used for normal building environment evaluation while the SET is mainly for air movement evaluation. Considering the limited space and the need for the coming sections, we mainly emphasize the PMV equations and their derivations. For other indexes, please refer to relevant literature.

PMV uses six parameters (e.g. air temperature t_a, mean radiant temperature t_r, relative humidity RH, air velocity v, clothing insulation I, and metabolic rate m) to establish the human body heat balance equation (see Eq. 1.1). Then, it correlates human body heat load with subjective thermal sensations according to climate chamber human subjects test results. A detailed derivation of PMV can be found in reference [11, 46]. Its calculating code can be found in ASHRAE Standard 55, GB/T 50785 and other standards. A web site to calculate PMV can be found in [57].

Table 1.1 Comparison of thermal environment evaluation indexes

Indexes	Input parameters	Major features
PMV [11]	I, M, t_a, t_r, RH, v	Calculate human body heat balance state, suitable for the steady-state neutral thermal environment
t_{op} [51]	t_a, t_r	Consider radiation temperature and air temperature
SET [52–54]	t_a, t_r, RH, v, I, M	Calculate human body heat balance with consideration of air movement based on the two-node model
UTCI [55]	t_a, t_r, RH, v, I, M	Calculate human body heat balance based on the multi-node physiological thermal regulation model
WBGT [56]	t_a, t_r, RH, v	Suitable for outdoor thermal comfort evaluation with consideration of solar radiation and wind speed

$$\begin{aligned}\text{PMV} = & \left(0.303\text{e}^{-0.036\text{M}} + 0.0275\right)\{\text{M} - \text{W} - 3.05[5.733 - 0.007(\text{M} - \text{W}) - P_\text{a}] \\ & - 0.42(\text{M} - \text{W} - 58.2) - 0.0173\text{M}(5.867 - P_\text{a}) - 0.0014\text{M}(34 - t_\text{a}) \\ & - 3.96 \times 10^{-8} f_\text{cl}\left[(t_\text{cl} + 273)^4 - (t_\text{r} + 273)^4\right] - f_\text{cl} h_\text{c}(t_\text{cl} - t_\text{a})\right\} \end{aligned} \quad (1.1)$$

In the equation, P_a is partial pressure of water vapor in air (Pa), t_a is ambient air temperature (°C), f_{cl} is the ratio of dressed human body surface area to the naked human body surface area, t_{cl} is outer surface temperature of clothing (°C), t_r is mean radiant temperature (°C), h_c is convective heat transfer coefficient of clothing outer surface (W/(m^2 K)).

PMV can predict the thermal sensation of a group of people in a given thermal condition. But due to large individual difference in thermal sensation between people, the statistical PPD index was proposed to predict the proportion of unsatisfied people in a given environment. In general, there is a quantitative relationship between PMV and PPD, as shown in Eq. 1.2.

$$\text{PPD} = 100 - 95^{\{-(0.03353\text{PMV}^4 + 0.2179\text{PMV}^2)\}} \quad (1.2)$$

Figure 1.11 shows the comfort zone of indoor thermal environment based on PMV calculation in ASHRAE Standard 55. In summer, when the clothing insulation is 0.5 clo and the relative humidity is 50%, the comfortable temperature range is 24–27 °C. In winter, when the clothing insulation is 1.0 clo and the relative humidity is 50%, the indoor comfortable temperature ranges from 20.5 to 24.5 °C.

Based on PMV-PPD calculation, many comfort evaluation standards classify indoor thermal conditions into different grades. The higher the grade, the narrower the range of PMV is allowed to deviate from thermal neutrality, leading to a stricter indoor temperature limit. As shown in Table 1.2, the grade I in ISO7730 requires to control the indoor temperature constantly, only 0.2 PMV fluctuation is allowed.

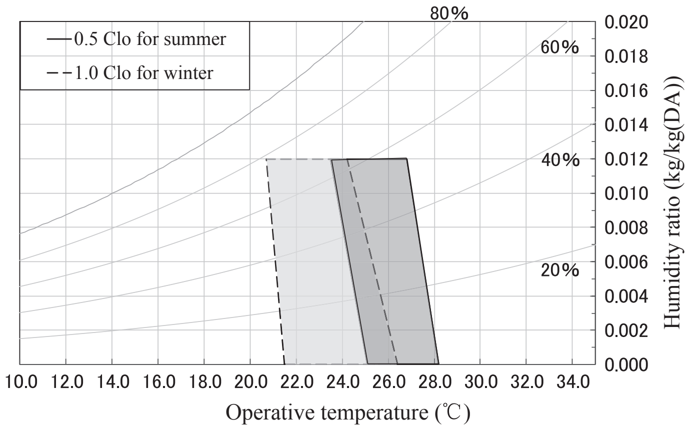


Fig. 1.11 Thermal comfort zone in ASHRAE standard 55