2 A review of thermal comfort

2.1 Human thermal comfort

Thermal comfort is defined as “that state of mind which expresses satisfaction with the thermal environment” (ANSI/ASHRAE, 2017). The definition of thermal comfort leaves open as to what is meant by condition of mind or satisfaction, but it correctly emphasizes that the judgment of comfort is a cognitive process involving many inputs related to physical, physiological, psychological, and other factors (Lin & Deng, 2008). People are always in an internal or external thermal environment. The human body produces heat and exchanges heat with the external environment. During normal activities these processes result in an average core body temperature of approximately 37 °C (Prek, 2005). This stable core body temperature is essential for our health and well-being. Our thermal interaction with the environment is directed towards maintaining this stability in a process called “thermoregulation” (Nicol, Humphreys, & Roaf, 2012).

Thermal comfort plays an important role in the energy consumption of buildings. So, researchers spent decades to find the appropriate approaches and models which evaluate and predict thermal comfort. A literature review of the current knowledge on thermal comfort shows two different approaches for thermal comfort, each one with its potentialities and limits: the heat-balance model and the adaptive model (Doherty & Arens, 1988). The heat-balance approach is based on analysis of the heat flows in and around the body and resulted in a model based on physics and physiology. Data from climate chamber studies was used to support this model. The best well-known heat-balance models are the predicted mean vote (PMV) (Fanger, 1970) and the standard effective temperature (SET) (Gagge, Fobelets, & Berglund, 1986). The PMV model is particularly important because it forms the basis for most national and international comfort standards. The adaptive approach is based on field surveys of people's response to the environment, using statistical analysis and leads to an "empirical" model (Nicol et al., 2012).

2.2 The heat balance approach to thermal comfort

In 1962, Macpherson defined the following six factors which affect the thermal sensation. Air temperature, radiant temperature, humidity and air movement are the four basic environmental variables that effect the human response to thermal environments, and metabolic heat generated by human activity and clothing are the two personal variables (Lin & Deng, 2008). Fanger (1970) developed the theory of human body heat exchange and built the thermal balance equations. According to Fanger (1970), the requirements for steady-state thermal comfort are: (i) the body is in heat balance, (ii) mean skin temperature and sweat rate, influencing this heat balance, are within certain limits, and (iii) no local discomfort exists.

For practical applications, in which subjects do not feel neutral, an extension of the comfort equation was needed. By combining various experimental studies in the climate chambers involving 1396 subjects, Fanger (1970) expanded his comfort equation to the PMV index. The PMV index predicts the mean response of a large group of people according to the seven-point ASHRAE thermal sensation scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot). PMV is a function of the six factors mentioned above. PMV has been extended to predict the proportion of the group who would be dissatisfied with the environment in terms of PPD. The PPD predicts the percentage of the people who voted outside the central three points on the ASHRAE scale (votes -3, -2, +2, +3) which were counted as dissatisfied. The value of PPD is calculated from the value of the PMV.

The PMV (PPD) model of thermal comfort has been used more than 40 years worldwide to assess thermal comfort. Many studies have given support to the PMV model while others showed discrepancies (Howell & Kennedy, 1979; Humphreys & Nicol, 2002; van Hoof, 2008). The main debate focuses on two subjects: the PMV model's validity and its application range. As the PMV model is derived from steady-state conditions in climate chambers and assumed clothing insulation and metabolic rate, the application range is limited. In practice, differences in the perception of

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the thermal environment were found among occupants of naturally ventilated (also referred to as free-running), fully air-conditioned and mixed mode or hybrid buildings (De Dear, Arens, Hui, & Oguro, 1997). It was found that for naturally ventilated buildings the indoor temperature in which is regarded as most comfortable increased significantly in warmer climatic contexts, and decreased in colder climate zones (De Dear, 2004). Conditions in passive buildings often cannot be controlled to the same extent as in buildings with mechanical air conditioning. Using natural phenomena such as wind, sun and outdoor temperature, such buildings cannot be closely regulated to a single temperature in the same way as those with fully mechanical systems. Therefore, the model based on heat balance approach is appropriate for mechanical heating or cooling buildings but not for free running passive buildings (Nicol & Roaf, 2007).

2.3 The adaptive approach to defining thermal comfort

The adaptive approach is based on field surveys of people's responses to the environment using statistical analysis and is called the "empirical" model (Nicol et al., 2012).

Field survey

A field survey is the basic tool of the adaptive approach (Humphreys, 1995).
A field survey of thermal comfort is an in situ poll of comfort (7-point ASHRAE scale of thermal sensation) among a given population together with simultaneous measurements of the environmental conditions (Nicol et al., 2012). Compared to the climate chamber method, participants wear their normal clothing and go about their usual work. The researcher uses statistical methods to analyse the data, using the natural variability of thermal conditions. The aim is to find the temperature of combination of thermal variables (temperature, humidity, air velocity) which subjects consider "neutral" or "comfortable". This analysis is then used to predict the "comfort temperature" of "comfort conditions" which will be found acceptable in similar circumstances elsewhere (Nicol & Humphreys, 2002).

Indoor comfort and outdoor temperature from field survey

By collecting data from reports of field surveys from all over the world, Humphreys (1976) first found that the comfort temperature is closely correlated with the mean indoor temperature measured. After that, it was found that there was also a strong relationship between the indoor comfort temperature and the outdoor temperature. Humphreys (1978) produced the well-known graph to show the relationship between the indoor comfort temperature and the outdoor temperature based on the field survey data from the period during 1935-1975 (figure 2.1). The relationship for the free-running buildings was closely linear. For heated and cooled buildings, the relationship is more complex (Nicol & Humphreys, 2002). Michael Humphreys (1978) gave the linear relationship between comfort temperature and monthly mean outdoor air temperature as the following equation:

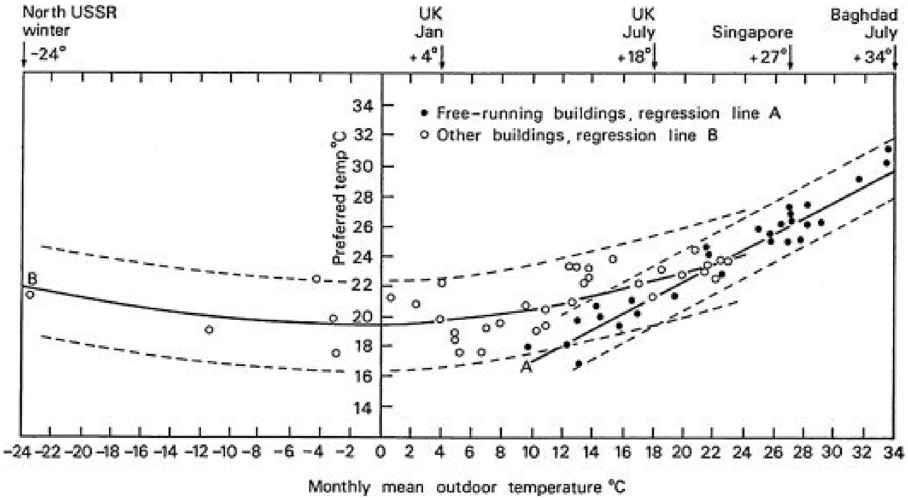

FIG. 2.1 Humphreys' graph for neutral/preferred temperature and the mean outdoor temperature (Humphreys, 1978)

$T_n=11.9+0.534*T_o$ (coefficient of determination, $R^2=0.97$)

Where:

T_n= neutral or preferred indoor temperature (°C);

T_o = outdoor monthly mean air temperature (°C);

The linear relationship between comfort temperature and the corresponding mean outdoor air temperature was also found and developed by Auliciems (1981) and De Dear and Brager (1998) based on different databases. The general equation can be expressed as:

$$T_{comf}=A*T_{out,m}+B$$

where

T_{comf} = comfort temperature (°C);

$T_{out,m}$ = monthly mean out-door air temperature (°C);

A, B = constants.

Adaptive principle

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Nicol et al., 2012).

People react in one of two principal ways corresponding to three categories: physiological adaptation, psychological adaptation and behavioural adaptation (Roaf, Nicol, Humphreys, Tuohy, & Boerstra, 2010). All of the three adaptations are related to the local climate, social and culture environment in where the subjects live. Behavioural adaptation is the most dominant factor in which people adjust their body heat balance to maintain thermal comfort through change “themselves” or the environment. People change “themselves” to avoid discomfort in the prevailing conditions: in many cases, this is through clothing adjustments, but also by other means - for instance, changes in posture (Raja & Nicol, 1997) or activity; people change the environment to keep thermal comfort, such as opening windows (to change temperature and air movement), drawing blinds (to reduce incoming radiation) or changing their location to a more comfortable spot in the room. The use of mechanical systems such as heating, cooling or fans can also be seen as examples of adaptive behaviour (Nicol & Humphreys, 2004). Nicol et al. (2012) categorized the adaptive actions as five basic types:

1. Regulating the rate of internal heat generation
2. Regulating the rate of body heat loss
3. Regulating the thermal environment

4 Selecting a different thermal environment
5 Modifying the body's physiological comfort conditions

Assuming that these responses are, on the whole, successful, the outcome of adaptive behaviours that subjects report themselves to be comfortable at a temperature which is typical of what they would expect to experience in their normal environment their 'customary' temperature, within a known behavioural lifestyle (Nicol & Roaf, 2007). The comfort temperature is a result of the interaction between the subjects and the building or other environment they occupy (Nicol & Humphreys, 2002). This comfort temperature is not static, it can change, for instance, season and the weather outside, or the location of a person's work.

Adaptive comfort model in design Standards

In different countries and regions, there are different standards for building design for thermal comfort specifically. But most of them are originated from the three well-known and widely used international standards: ISO Standard 7730, ANSI/ASHRAE Standard 55 and European standard EN 15251. At present, only two standards include adaptive comfort components:

1 ANSI/ASHRAE 55 adaptive thermal comfort standard

The ANSI/ASHRAE Standard 55 is the first international standard including adaptive comfort model to evaluate the indoor thermal comfort. This standard was put forward following the extensive work of De Dear and Brager (2002) and using data collected in ASHRAE project RP 884 (De Dear & Brager, 1998) for the "naturally conditioned" buildings. The standard used the equation, which resulted from more than 21,000 observations of thermal sensation from field study in 160 buildings from 9 countries to express the relationship between indoor thermal comfort temperature and outdoor temperature and defines zones within which 80 percent or 90 percent of building occupants might expect to find the conditions acceptable. Although ASHRAE 55 is an American national standard, because the field studies were sourced from different countries and regions, the adaptive model of ASHRAE 55 is regarded as a global implementation. The ANSI/ASHRAE 55 gave the optimal comfort temperature in occupant-controlled natural conditioned spaces as:

$$T_o = 0.31T_{out} + 17.8$$

Where:

T_o is the optimal temperature for comfort (°C);

T_{out} is the mean monthly outdoor air temperature for the survey in ANSI/ASHRAE 55 of 2004 and 2010, and the prevailing mean outdoor temperature ($t_{pma(out)}$) in ANSI/ASHRAE 55 of 2013 and 2017.

The prevailing mean outdoor temperature ($t_{pma(out)}$) was written as (ANSI/ASHRAE, 2017):

$$t_{pma(out)}=(1-\alpha).[t_{e(d-1)}+ \alpha\ t_{e(d-2)}+ \alpha^2\ t_{e(d-3)}+ \alpha^3\ t_{e(d-4)}+\ldots]$$

where α is a constant between 0 and 1 that controls the speed at which the running mean responds to changes in weather (outdoor temperature); $t_{e(d-1)}$ represents the mean daily outdoor temperature for the previous day, $t_{e(d-2)}$ is the mean daily outdoor temperature for the day before that, and so on. The prevailing mean outdoor temperature should be larger than 10 °C and lower than 33.5 °C.

The current version of ANSI/ASHRAE 55 of 2017 gives the acceptable operative temperature ranges in figure 2.2. The equation is:

$$T_o=0.31T_{out}+17.8\pm T_{lim}$$

Where T_o gives the limits of the acceptable zones and T_{lim} is the rang of acceptable temperature (for 80 percent or 90 percent of the occupants being satisfied). The given limits are $T_{lim}(80\%)=3.5$ °C and $T_{lim}(90\%)=2.5$ °C.

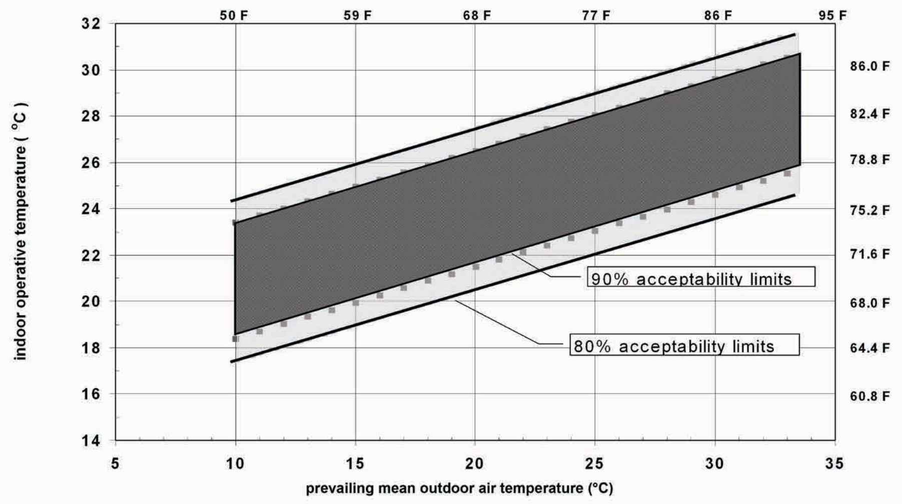

FIG. 2.2 Acceptable operative temperature ranges for naturally conditioned spaces (ANSI/ASHRAE, 2017)

2 EN 15251 adaptive thermal comfort standard

The adaptive standard in EN 15251 is similar to that in ASHRAE Standard 55, but using the database from the European SCATs project (Nicol & McCartney, 2001) that was collected from five European countries (France, Greece, Portugal, Sweden and UK) instead of the ASHRAE project RP 884 database. The optimal indoor comfort temperature in EN15251 (2007) is:

$$\theta_o = 0.33\ \theta_{rm} + 18.8$$

Where:

θ_o is the operative temperature (°C);

θ_{rm} is the running mean outdoor temperature. It was written as:

$$\theta_{rm(ed)} = (1-\alpha).[\ \theta_{ed-1} + \alpha\ \theta_{ed-2} + \alpha^2\ \theta_{ed-3} + \alpha^3\ \theta_{ed-4} + \ldots]$$

where α is a constant between 0 and 1, recommended 0.8; θ_{ed-n} represents the mean daily outdoor temperature for n-days prior the day in question. An approximate equation is provided when full records of daily running mean outdoor temperature are not available as:

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

The acceptable indoor operative temperature ranges from the optimal temperature for comfort temperature mentioned above is divided into four categories (figure 2.3). The calculation of the upper and lower limits of the different categories shall be expressed as the following equation:

Upper limit of category III: $\theta_{omax}=0.33\ \theta_{rm}+18.8+4$

Upper limit of category II: $\theta_{omax}=0.33\ \theta_{rm}+18.8+3$

Upper limit of category I: $\theta_{omax}=0.33\ \theta_{rm}+18.8+2$

Lower limit of category I: $\theta_{omin}=0.33\ \theta_{rm}+18.8-2$

Lower limit of category II: $\theta_{omin}=0.33\ \theta_{rm}+18.8-3$

Lower limit of category III: $\theta_{omin}=0.33\ \theta_{rm}+18.8-4$

These limits apply when $10< \theta_{rm}<30$°C for the upper limit and $15< \theta_{rm}<30$°C for the lower limit.

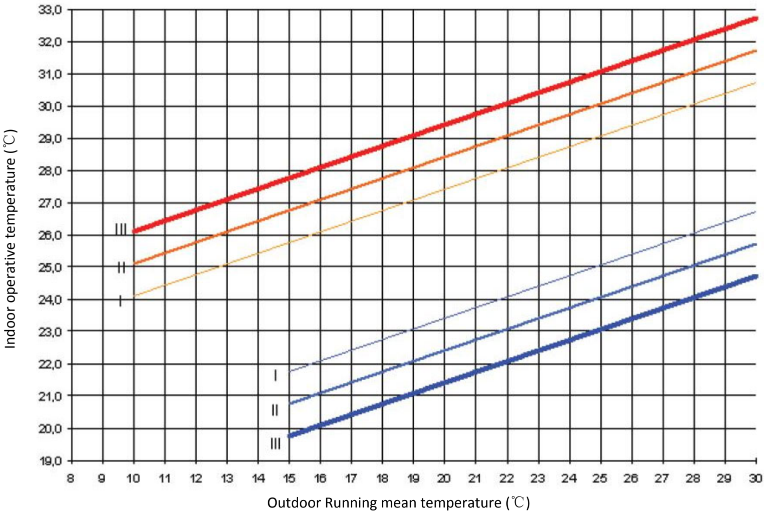

FIG. 2.3 Acceptable operative temperature ranges for naturally conditioned spaces (EN15251, 2007)

2.4 Thermal comfort in a hot climate

Selecting a thermal comfort model is important for saving cooling energy consumption and to evaluate occupants' thermal comfort correctly. Attia and Carlucci (2015) compared the different models used in the climates. It was found that the variation in the different comfort models is very large. The adaptive models (both ASHRAE 55 and EN 15251) predict a wider range of comfort temperatures than the Fanger's model. The adaptive comfort model is thought to be more appropriate for mixed-mode non air-conditioned buildings in hot climates (De Dear, 1999; Pfafferott, Herkel, Kalz, & Zeuschner, 2007; Rijal, Humphreys, & Nicol, 2008). The adaptive model is based on field surveys, including field surveys in a hot climate such as India, Iraq and Singapore. The field surveys indicated that the PMV model cannot predict the thermal comfort correctly in the hot climates, especially for free-running buildings. The subjects can be comfortable at temperatures up to or even exceeding 30°C (Nicol, 2004). The adaptive model has great energy saving and mitigation potential, especially in warmer climates, where the building cooling load is the major design consideration (Wan, Li, Pan, & Lam, 2012). The energy savings as a result of using an adaptive comfort model was estimated to be 10-18% of the overall cooling load (Attia & Carlucci, 2015).

For the application of the adaptive thermal comfort model in a hot and humid climate, the effect of air movement and humidity are considered. In hot climate regions, especially for free-running or naturally ventilated buildings, the influence of humidity and wind velocity on occupants' thermal comfort sensation is larger than in other climate regions and in conditioned buildings. The cooling effect of air movement depends on not only air velocity, but also the temperature, humidity and radiation balance, as well as on the activity (metabolic rate) and clothing of the individual (Szokolay, 2000). Studies done in different climates show that occupants prefer larger air movement and thermal comfort ranges can expand with the aid of air movement (Mishra & Ramgopal, 2013). In hot and humid climates, air movement can enhance convective heat transfer from the skin and increase the evaporation of sweat. Occupants appreciate air movement even when it is not necessary for cooling (Zhang et al., 2007). For air movement, Nicol (2004) proposes that there can be an allowance on the comfort temperature depending on the velocity of air movement that is felt by the occupants. Other researchers also proposed equations for the influence of the wind velocity on the thermal comfort in a hot climate (table 2.1).

TABLE 2.1 Effects of air movement on comfort temperature

Source	Comfort temperature Correction for enhanced air velocity	Conditions
ASHRAE Standard 55 (ANSI/ ASHRAE, 2017)	ΔT=1.2 ΔT=1.8 ΔT=2.2	0.3m/s<Va<0.6m/s 0.6m/s<Va<0.9m/s 0.9m/s<Va<1.2m/s
EN15251-2007 (EN15251, 2007), Nicol (Nicol, 2004)	$\Delta T = 7 - \frac{50}{4 + 10V_a^{0.5}}$	0.1m/s<Va
Szokolay (Szokolay, 2000)	$\Delta T = 6V_e\text{-}1.6(V_e)^2, V_e = V\text{-}0.2\ \mathrm{m/s}$	V<2m/s
China (Su, Zhang, & Gao, 2009)	$\Delta T = -4(\varphi\text{-}70\%) + \frac{0.55\mathrm{V}}{0.15}, \mathrm{T} > 28℃$ $\Delta T = \frac{0.55V}{0.15}, \mathrm{T} < 28℃$	V<0.8m/s

Here ΔT is the raise in comfort temperature (°C); T is the indoor air temperature (°C); Va is the air velocity (m/s); V is the air velocity at the body surface (m/s); ϕ is the relative humidity (if less than 70%, ϕ =70%)

The influence of humidity on thermal comfort is more difficult to determine. Humidity has been investigated in a number of field surveys in hot climates, and although the humidity is found to have a significant effect on the comfort temperature, the size of the effect is generally small, and further research is needed (Nicol, 2004).

2.5 Thermal comfort in outdoor and semi-outdoor spaces

To create a sustainable and comfortable outdoor built environment is one of the core issues in urban planning. At present, the outdoor thermal comfort in public spaces-pedestrian streets, public squares and gardens, is the common focus of urban planning. As cities expand and the population in the cities rises, many issues related to sustainable development extend to the urban scale. Consequently, the research of the urban microclimate and outdoor thermal comfort are becoming more and more important. However, compared to indoor thermal comfort for which the quantitatively analysis is reasonable well established, it is still a challenge to quantitatively describe the outdoor thermal comfort (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016). This is due to the great complexity of the outdoor environment in terms of variability, temporally and spatially, and the large range of activities people are engaged in (Nikolopoulou, Baker, & Steemers, 2001). The variability in exposure time influences the human capacity to acclimatize, and underlines the need for non-steady state models to quantify outdoor human comfort (Höppe, 2002). In the outdoor environment, people are directly exposed to local microclimate conditions of solar radiation, shading and changes in wind direction and speed (Chen & Ng, 2012). People carry out various activities, and each person has a different thermal history, memory and expectations (Nikolopoulou et al., 2001).

For the evaluation and prediction of outdoor thermal comfort, Nagano and Horikoshi (2011), Chen and Ng (2012) and Coccolo et al. (2016) have done a review of outdoor thermal comfort models. The major outdoor thermal comfort models are steady-state models. These models are based on the assumption that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium, and they provide numerical solutions to the energy balance equations governing thermoregulation (Chen & Ng, 2012). Even though the PMV-PPD index was originally developed for the evaluation of indoor thermal comfort, it is also commonly adopted in outdoor thermal comfort studies. The PET (Physiological Equivalent Temperature) (Mayer & Höppe, 1987) is another notable example of a steady-state model commonly used in outdoor thermal comfort research. PET is defined as the "air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed" (Höppe, 1999). The PET model is particularly suitable for the evaluation of the outdoor thermal comfort in that it translates the evaluation of a complex outdoor climatic environment to a simple indoor scenario on a physiologically equivalent basis that can be easily understood and interpreted (Chen & Ng, 2012). A further development of PET is mPET (modified PET) that improves the capacity of the model to react to the change of relative humidity and clothing insulation (Chen & Matzarakis, 2014). Some other steady-state models-thermal stress (ITS) (Givoni, 1976), the OUT-SET (Pickup & de Dear, 2000), the COMFA (Kenny, Warland, Brown, & Gillespie, 2009), and the UTCI (Jendritzky, de Dear, & Havenith, 2012) are also applied in the outdoor thermal comfort studies. However, the steady-state models cannot effectively account for the dynamic aspects of the course of human thermal adaption (Chen & Ng, 2012). Many researches are developing non-steady-state models for the evaluation of outdoor thermal comfort based on field studies.

Semi-outdoor spaces, which some researchers also call transitional spaces or buffer spaces, are spaces featuring a semi-enclosed wall or roof. Semi-outdoor spaces can flexibly connect the indoor spaces and outdoor spaces that make the spaces more diverse. The outside corridor, the terrace, the balcony and the veranda are the most common transitional spaces. Literature review revealed that only few studies

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focus on thermal comfort in these spaces. The field studies that were found were: a field study in Sydney Australia (Spagnolo & de Dear, 2003), two stadium case studies in Paris and Istanbul (Bouyer, Vinet, Delpech, & Carré, 2007), a space under a membrane in Japan (He & Hoyano, 2010), a field study in a workplace in Beirut (Ghaddar, Ghali, & Chehaitly, 2011), a field study in Taiwan (Hwang & Lin, 2007) and in Wuhan (Zhou, Chen, Deng, & Mochida, 2013). Nevertheless, there are no specific regulations and standards for the thermal comfort of such spaces, most of the studies use the outdoor thermal comfort models to evaluate the thermal comfort in semi-outdoor spaces.

2.6 The adaptive approach in China

2.6.1 Development of adaptive approach in China

Occupants' adaption in the thermal comfort study is investigated by Chinese researchers. Yang (2003) investigated the adaptive thermal comfort model of five typical cities in China and achieved a linear correlation between comfort temperature and outdoor temperature. A field study of a thermal environment was performed and an adaptive model was built in Shanghai (Ye et al., 2006). Han et al. (2007) discussed the inside thermal comfort of residences of three cities in the hot-humid climate of central southern China. It was found that only 48.2% of the measured variables are within the ASHRAE Standard 55-1992 summer comfort zone, but approximately 87.3% of the occupants perceived their thermal conditions acceptable, for subjects adapt to prevailing conditions. Han et al. (2009) investigated the occupants' thermal comfort and residential thermal environment conducted in an urban and a rural area in Hunan province and found the percentage of acceptable votes of rural occupants is higher than that of urban occupants at the same operative temperature. Wang, Zhang, Zhao, and He (2010) studied the thermal comfort for naturally ventilated residential buildings in Harbin. The acceptable air temperature range in winter and summer was identified. Thermal comfort in naturally ventilated buildings in the hot-humid area of China is investigated by Zhang, Wang, Chen, Zhang, and Meng (2010). The adaptive evidences were obtained for clothing adjustment, window opening and using fan, respectively, and a modified PMV model was validated to be applicable in NV buildings. Human thermal adaptive behaviour

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in naturally ventilated offices was studied in Changsha, China (Liu, Zheng, Deng, & Yang, 2012). Based on the survey, the characteristics of the thermal adaptive behaviour in the offices were revealed. A year-long field study of the thermal environment in university classrooms in Chongqing was done by Yao, Liu, and Li (2010). The adaptive thermal comfort zone for the naturally conditioned space for Chongqing has been proposed based on the field study results. Furthermore, Liu, Yao, Wang, and Li (2012) studied the occupants' adaptation in workplaces with non-central heating and cooling systems in Chongqing. They demonstrated that occupants are active players in environmental control and their adaptive responses are driven strongly by ambient thermal stimuli and vary from season to season and from time to time, even on the same day.

Some researchers found a linear correlation between the outdoor air temperature and comfort temperature corresponding to the local climate, culture and people's perception in different regions of China. Table 2.2 listed some of the major findings in terms of the linear relationship between the mean outdoor temperature T_{out} (°C) and the neutral or preferred indoor temperature T_n (°C).

TABLE 2.2 The major findings of the linear relationship between mean outdoor temperature and the neutral or preferred indoor temperature by different researchers in China

References	Equation	Location
Yang (2003)	$T_n = 0.30T_{out} + 19.7$	Five typical cities in China
Ye et al. (2006)	$T_n = 0.42T_{out} + 15.12$	Shanghai
Han (2007)	In city: $T_n = 0.67T_{out} + 10.32$ In rural: $T_n = 0.44T_{out} + 9.17$	"hot summer and cold winter" climate region
Wang et al. (2010)	$T_n = 0.468T_{out} + 11.80$	Harbin (summer)
Li (2008)	$T_n = 0.39T_{out} + 16.28$ (5.0°C-30.0°C.)	Chongqing

An interesting finding is by Su et al. (2009). He improved the study by Yang (2003) and proposed to add the effects of airflow velocity and relative humidity in the adaptive model. He considered that people will be more comfortable at the environment of temperatures over 26°C if they feel the wind. If the relative humidity exceeds 70%, the comfort temperature will ascend 0.4°C by a 10% increase of relative humidity on the premise that the indoor air temperature exceeds 28°C. The Comfort temperature will decrease 0.55 °C with a 0.15 m/s increase of airflow velocity. When the indoor air temperature is above and below 28°C, the thermal neutral temperature is thus improved to be as the following two equations respectively:

$$T_c=0.30T_o+19.7-4\ (\phi-70\%)+0.55v/0.15$$

$$T_c=0.30T_o+19.7+0.55v/0.15$$

Where T_c is the neutral or preferred indoor temperature (°C), T_o is the monthly mean outdoor temperature (°C), ϕ is the relative humidity (if less than 70%, ϕ = 70%), v is the airflow velocity along the body surface. The velocity on body surface should not be over 0.8 m/s (Su et al., 2009).

2.6.2 Adaptive approach in Chinese standard

China is classified into five climate zones (very cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and temperate zone) for building design according to the national “Standard of Climatic Regionalisation for Architecture” (GB50178, 1993). Li, Yao, Wang, and Pan (2014) performed a detailed introduction in the development process of the Chinese standard of indoor thermal comfort. Before the newest code “Evaluation standard for indoor thermal environments in civil buildings GB/T50785-2012”, which was published in May of 2012, the existing Chinese standards relevant to indoor environmental design and thermal comfort mainly adopted the international standards based on the PMV–PPD models. In the newest code of GB/T50785-2012, the thermal comfort for the heated and cooled spaces is based on the PMV-PPD models. However, for the free-running buildings, the code offers an adaptive comfort model for the evaluation of the indoor thermal environment. It includes two methods: a graphical method and a calculation method.

Graphical method

The graphical method is based on the adaptive thermal comfort model in ANSI/ASHRAE 55 (Li et al., 2014). In the graphical method, the operative temperature ranges were identified according to different climate zones (figure 2.4 (a)(b)). There are two categorizes for the acceptable operative temperature ranges: category I represents 90% occupant acceptability with the maximum temperature of 30°C and the minimum temperature of 18°C, and category II corresponds to 75-90% acceptability with the maximum temperature of 30°C and the minimum temperature of 16°C.

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The running mean of outdoor temperature (t_{op}) was written as:

$$t_{op}=(1-\alpha).(t_{ed-1}+\alpha\, t_{ed-2}+\alpha^2\, t_{ed-3}+\alpha^3\, t_{ed-4}+\alpha^4\, t_{ed-5}+\alpha^5\, t_{ed-6}+\alpha^6\, t_{ed-7})$$

where α is a constant between 0 and 1, and is recommended as 0.8; t_{ed-n} represents the mean daily outdoor temperature for n-days prior the day in question.

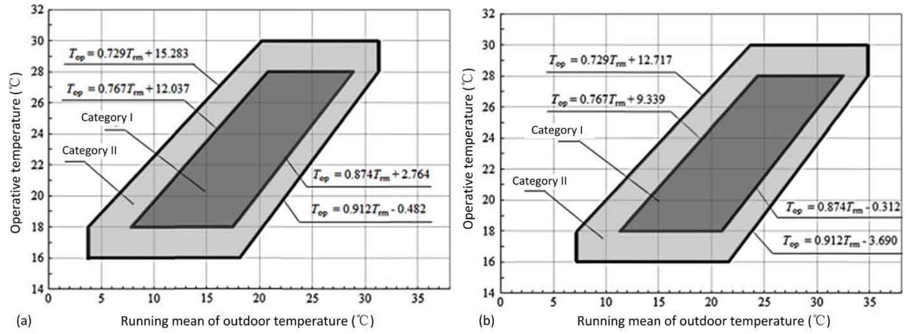

FIG. 2.4 (a) Acceptable operative temperature ranges of the thermal environment in free-running buildings in the very cold and cold zones (Top: operative temperature; Trm: running mean of outdoor temperature) (Li et al., 2014). (b) Acceptable operative temperature ranges of the thermal environment in free-running buildings in the hot summer and cold winter zone, the hot summer and warm winter zone and the mild zone (Top: operative temperature; Trm: running mean of outdoor temperature) (Li et al., 2014)

Calculation method

For the calculation method, the aPMV (adaptive prediction mean vote) was introduced. The aPMV (Yao, Li, & Liu, 2009) is the modification of the PMV model of the thermal comfort evaluation considering the adaption of occupants from field studies carried out in China between 2007 and 2011. The equation for aPMV is proposed as:

$$aPMV=\frac{PMV}{1+\lambda PMV}$$

where λ is the adaptive coefficient, which has a positive value when in warm conditions and a negative value when conditions are cool. Because the aPMV index is derived from Fanger's PMV, the input parameters (i.e. air temperature, mean radiation temperature, air speed, relative humidity, occupants' clothing insulation levels and metabolic rate) to PMV are also necessary for the calculation.

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2.7 Conclusion

Summarizing the current evaluation approaches in scientific research and design standards for thermal environment of occupants, both the PMV/PPD model and the adaptive model are important related to different environmental conditions, even though there are still some discussion between the two models. The PMV/PPD model predicts thermal sensation well in buildings with HVAC systems, however, field studies in warm climates in buildings without air-conditioning have shown to predict a warmer thermal sensation than the occupants actually feel (Brager & de Dear, 1998). The adaptive model is suitable for the evaluation of the free-running buildings which have great potential for energy conservation. However, more field studies are needed to validate the linear correlation between the outdoor temperature and comfort temperature respecting to different climatic, social and culture environments. In this thesis, the summer thermal comfort and passive cooling are focused on the free-running buildings, therefore, the adaptive thermal comfort approach is applied for the thermal environmental evaluation. The adaptive thermal comfort in ANSI/ASHRAE 55 standards, the Chinese standards and the local equation (Chongqing) for adaptive thermal comfort are all considered in the following studies.

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References

ANSI/ASHRAE. (2017). ASHRAE standard 55 Thermal Environmental Conditions for Human Occupancy GA, USA: ASHRAE Atlanta.

Attia, S., & Carlucci, S. (2015). Impact of different thermal comfort models on zero energy residential buildings in hot climate. *Energy and Buildings, 102*, 117-128. doi: 10.1016/j.enbuild.2015.05.017

Auliciems, A. (1981). Towards a psycho-physiological model of thermal perception. *Int J Biometeorol, 25*(2), 109-122.

Bouyer, J., Vinet, J., Delpech, P., & Carré, S. (2007). Thermal comfort assessment in semi-outdoor environments: Application to comfort study in stadia. *Journal of Wind Engineering and Industrial Aerodynamics, 95*(9-11), 963-976. doi: 10.1016/j.jweia.2007.01.022

Brager, G. S., & de Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and* Buildings, 27(1), 83-96. doi: http://dx.doi.org/10.1016/S0378-7788(97)00053-4

Chen, L., & Ng, E. (2012). Outdoor thermal comfort and outdoor activities: A review of research in the past decade. Cities, 29(2), 118-125. doi: http://dx.doi.org/10.1016/j.cities.2011.08.006

Chen, Y.-C., & Matzarakis, A. (2014). Modification of physiologically equivalent temperature. Journal of Heat Island Institute International Vol, 9, 2.

Coccolo, S., Kämpf, J., Scartezzini, J.-L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. Urban Climate, 18, 33-57. doi: http://dx.doi.org/10.1016/j.uclim.2016.08.004

De Dear, R. (1999). *Adaptive thermal comfort in natural and hybrid ventilation.* Paper presented at the First International One day Forum on Natural and Hybrid Ventilation, HybVent Forum.

De Dear, R. (2004). Thermal comfort in practice. *Indoor Air, 14*(s7), 32-39.

De Dear, R., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans, 104*, 145-167.

De Dear, R. J., Arens, E., Hui, Z., & Oguro, M. (1997). Convective and radiative heat transfer coefficients for individual human body segments. *Int J Biometeorol, 40*(3), 141-156.

De Dear, R. J., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. [Article; Proceedings Paper]. *Energy and Buildings, 34*(6), 549-561. doi: 10.1016/s0378-7788(02)00005-1

Doherty, T., & Arens, E. A. (1988). Evaluation of the physiological bases of thermal comfort models. ASHRAE Transactions, Vol. 94, Part 1, 15 pp. ttps://escholarship.org/uc/item/6pq3r5pr

EN15251. (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: European committee for standardisation.

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

Gagge, A. P., Fobelets, A., & Berglund, L. (1986). A standard predictive index of human response to the thermal environment. *ASHRAE Trans.;(United States), 92*(CONF-8606125-).

GB50178. (1993). Standard of Climate Regionalization for Architecture, National Standard. Beijing, China: Chinese Plan Publication House.

Ghaddar, N., Ghali, K., & Chehaitly, S. (2011). Assessing thermal comfort of active people in transitional spaces in presence of air movement. *Energy and Buildings, 43*(10), 2832-2842.

Givoni, B. (1976). *Man, climate and architecture.* London: Applied Science Publisher.

Han, J., Yang, W., Zhou, J., Zhang, G., Zhang, Q., & Moschandreas, D. J. (2009). A comparative analysis of urban and rural residential thermal comfort under natural ventilation environment. *Energy and Buildings, 41*(2), 139-145. doi: 10.1016/j.enbuild.2008.08.005

Han, J., Zhang, G., Zhang, Q., Zhang, J., Liu, J., Tian, L., . . . Moschandreas, D. J. (2007). Field study on occupants' thermal comfort and residential thermal environment in a hot-humid climate of China. *Building and Environment, 42*(12), 4043-4050. doi: 10.1016/j.buildenv.2006.06.028

He, J., & Hoyano, A. (2010). Measurement and evaluation of the summer microclimate in the semi-enclosed space under a membrane structure. [Article]. *Building and Environment, 45*(1), 230-242. doi: 10.1016/j.buildenv.2009.06.006

TOC

Höppe, P. (1999). The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol, 43*(2), 71-75.

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings, 34*(6), 661-665. doi: http://dx.doi.org/10.1016/S0378-7788(02)00017-8

Howell, W. C., & Kennedy, P. A. (1979). Field validation of the Fanger thermal comfort model. Human Factors, 21(2), 229-239.

Humphreys, M. (1978). Outdoor temperatures and comfort indoors. Batiment International, Building Research and Practice, 6(2), 92-92. doi: 10.1080/09613217808550656

Humphreys, M. (1995). Thermal comfort temperatures and the habits of Hobbits. Standards for Thermal Comfort: Indoor Air Temperature Standards for the 21st Century, 3-13.

Humphreys, M. A. (1976). Field studies of thermal comfort compared and applied. The Building Services Engineer, 44, 27.

Humphreys, M. A., & Fergus Nicol, J. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and Buildings, 34(6), 667-684. doi: http://dx.doi.org/10.1016/S0378-7788(02)00018-X

Hwang, R.-L., & Lin, T.-P. (2007). Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions. Architectural Science Review, 50(4), 357-364.

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI—Why another thermal index? Int J Biometeorol, 56(3), 421-428.

Kenny, N. A., Warland, J. S., Brown, R. D., & Gillespie, T. G. (2009). Part A: Assessing the performance of the COMFA outdoor thermal comfort model on subjects performing physical activity. Int J Biometeorol, 53(5), 415.

Li, B., Yao, R., Wang, Q., & Pan, Y. (2014). An introduction to the Chinese Evaluation Standard for the indoor thermal environment. Energy and Buildings, 82, 27-36. doi: 10.1016/j.enbuild.2014.06.032

Li, Y. (2008). The study of the ventilation period and the effectiveness of control in residential building of Chongqing. master, Chongqing University, Chongqing.

Lin, Z., & Deng, S. (2008). A study on the thermal comfort in sleeping environments in the subtropics—developing a thermal comfort model for sleeping environments. Building and Environment, 43(1), 70-81.

Liu, J., Yao, R., Wang, J., & Li, B. (2012). Occupants' behavioural adaptation in workplaces with non-central heating and cooling systems. Applied Thermal Engineering, 35, 40-54. doi: 10.1016/j.applthermaleng.2011.09.037

Liu, W., Zheng, Y., Deng, Q., & Yang, L. (2012). Human thermal adaptive behaviour in naturally ventilated offices for different outdoor air temperatures: A case study in Changsha China. *Building and Environment, 50*, 76-89. doi: 10.1016/j.buildenv.2011.10.014

Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and applied climatology, 38*(1), 43-49.

Mishra, A. K., & Ramgopal, M. (2013). Field studies on human thermal comfort — An overview. *Building and Environment, 64*, 94-106. doi: 10.1016/j.buildenv.2013.02.015

Nagano, K., & Horikoshi, T. (2011). New index indicating the universal and separate effects on human comfort under outdoor and non-uniform thermal conditions. Energy and Buildings, 43(7), 1694-1701. doi: http://dx.doi.org/10.1016/j.enbuild.2011.03.012

Nicol, F. (2004). Adaptive thermal comfort standards in the hot–humid tropics. *Energy and Buildings, 36*(7), 628-637. doi: http://dx.doi.org/10.1016/j.enbuild.2004.01.016

Nicol, F., Humphreys, M. A., & Roaf, S. (2012). *Adaptive thermal comfort: principles and practice* London and New York: Routledge.

Nicol, F., & Roaf, S. (2007). Progress on passive cooling: adaptive thermal comfort and passive architecture. *Advances in Passive Cooling, Earthscan, London, UK*, 1-29.

Nicol, J., & McCartney, K. (2001). Final report of Smart Controls and Thermal Comfort (SCATs) Project. Report to the European Commission of the Smart Controls and Thermal Comfort project: Oxford Brookes University, UK.

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings, 34(6), 563-572. doi: http://dx.doi.org/10.1016/S0378-7788(02)00006-3

Nicol, J. F., & Humphreys, M. A. (2004). A Stochastic Approach to Thermal Comfort--Occupant Behavior and Energy Use in Buildings. ASHRAE Transactions, 110(2).

Nikolopoulou, M., Baker, N., & Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter. Solar Energy, 70(3), 227-235. doi: http://dx.doi.org/10.1016/S0038-092X(00)00093-1

Pfafferott, J. Ü., Herkel, S., Kalz, D. E., & Zeuschner, A. (2007). Comparison of low-energy office buildings in summer using different thermal comfort criteria. Energy and Buildings, 39(7), 750-757. doi: http://dx.doi.org/10.1016/j.enbuild.2007.02.005

Pickup, J., & de Dear, R. (2000). An outdoor thermal comfort index (OUT_SET*)-part I-the model and its assumptions. Paper presented at the Biometeorology and urban climatology at the turn of the millenium. Selected papers from the Conference ICB-ICUC.

Prek, M. (2005). Thermodynamic analysis of human heat and mass transfer and their impact on thermal comfort. International Journal of Heat and Mass Transfer, 48(3), 731-739. doi: http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.09.006

Raja, I. A., & Nicol, F. (1997). A technique for recording and analysis of postural changes associated with thermal comfort. Applied ergonomics, 28(3), 221-225.

Rijal, H., Humphreys, M., & Nicol, J. (2008). How do the occupants control the temperature in mixed-mode buildings? Predicting the use of passive and active controls. Paper presented at the Proceeding of conference: Air Conditioning and the Low Carbon Cooling Challenge, Windsor, UK.

Roaf, S., Nicol, F., Humphreys, M., Tuohy, P., & Boerstra, A. (2010). Twentieth century standards for thermal comfort: promoting high energy buildings. Architectural Science Review, 53(1), 65-77.

Spagnolo, J., & de Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Building and Environment, 38(5), 721-738. doi: 10.1016/s0360-1323(02)00209-3

Su, X., Zhang, X., & Gao, J. (2009). Evaluation method of natural ventilation system based on thermal comfort in China. Energy and Buildings, 41(1), 67-70. doi: http://dx.doi.org/10.1016/j.enbuild.2008.07.010

Szokolay, S. V. (2000). Dilemmas of warm humid climate house design. Paper presented at the Proceedings of PLEA 2000 Architecture, City, Environment, Cambridge,England.

Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: comfort for all? [Review]. Indoor Air, 18(3), 182-201. doi: 10.1111/j.1600-0668.2007.00516.x

Wan, K. K., Li, D. H., Pan, W., & Lam, J. C. (2012). Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. Applied Energy, 97, 274-282.

Wang, Z., Zhang, L., Zhao, J., & He, Y. (2010). Thermal comfort for naturally ventilated residential buildings in Harbin. Energy and Buildings, 42(12), 2406-2415. doi: http://dx.doi.org/10.1016/j.enbuild.2010.08.010

Yang, L. (2003). Climatic analysis techniques and architectural design strategies for bioclimatic design. Xi'an University of Architecture and Technology, Xi'an.

Yao, R., Li, B., & Liu, J. (2009). A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV). Building and Environment, 44(10), 2089-2096. doi: http://dx.doi.org/10.1016/j.buildenv.2009.02.014

Yao, R., Liu, J., & Li, B. (2010). Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms. *Applied Energy, 87*(3), 1015-1022. doi: 10.1016/j.apenergy.2009.09.028

Ye, X. J., Zhou, Z. P., Lian, Z. W., Liu, H. M., Li, C. Z., & Liu, Y. M. (2006). Field study of a thermal environment and adaptive model in Shanghai. [Research Support, Non-U.S. Gov't]. *Indoor Air, 16*(4), 320-326. doi: 10.1111/j.1600-0668.2006.00434.x

Zhang, H., Arens, E., Fard, S. A., Huizenga, C., Paliaga, G., Brager, G., & Zagreus, L. (2007). Air movement preferences observed in office buildings. [Research Support, Non-U.S. Gov't

Research Support, U.S. Gov't, Non-P.H.S.]. *Int J Biometeorol, 51*(5), 349-360. doi: 10.1007/s00484-006-0079-y

Zhang, Y., Wang, J., Chen, H., Zhang, J., & Meng, Q. (2010). Thermal comfort in naturally ventilated buildings in hot-humid area of China. *Building and Environment, 45*(11), 2562-2570. doi: http://dx.doi.org/10.1016/j.buildenv.2010.05.024

Zhou, Z., Chen, H., Deng, Q., & Mochida, A. (2013). A field study of thermal comfort in outdoor and semi-outdoor environments in a humid subtropical climate city. *Journal of Asian Architecture and Building Engineering, 12*(1), 73-79.